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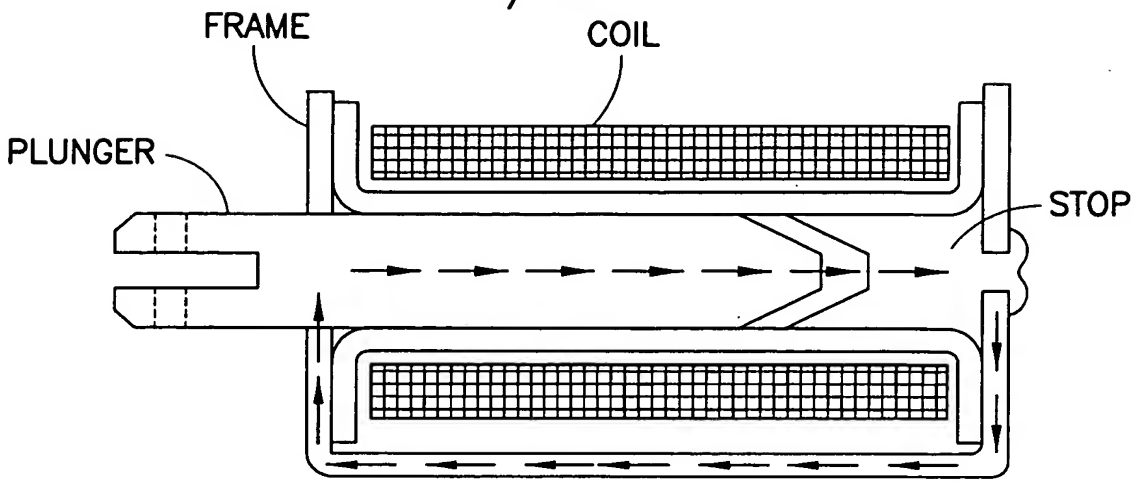


FIG. 1A

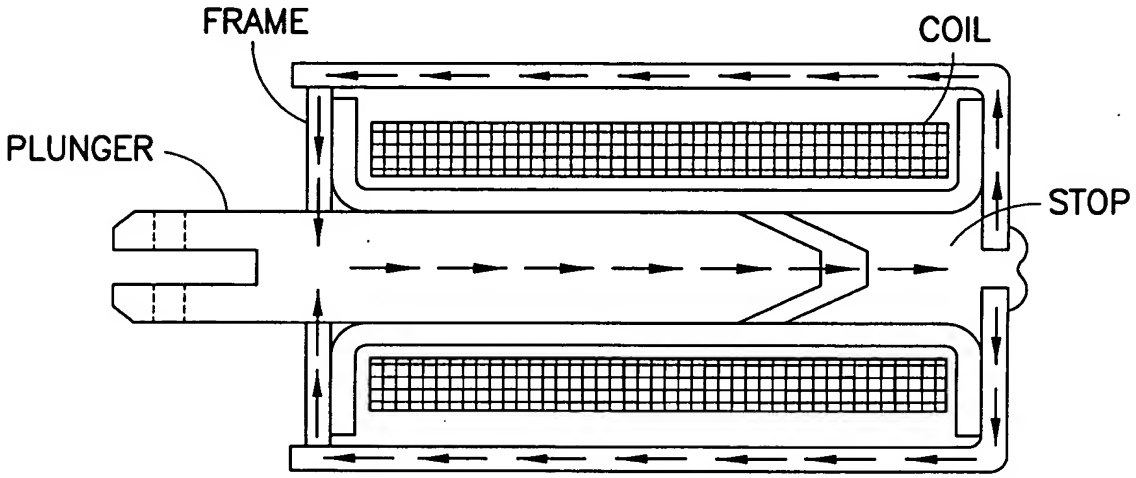


FIG. 1B

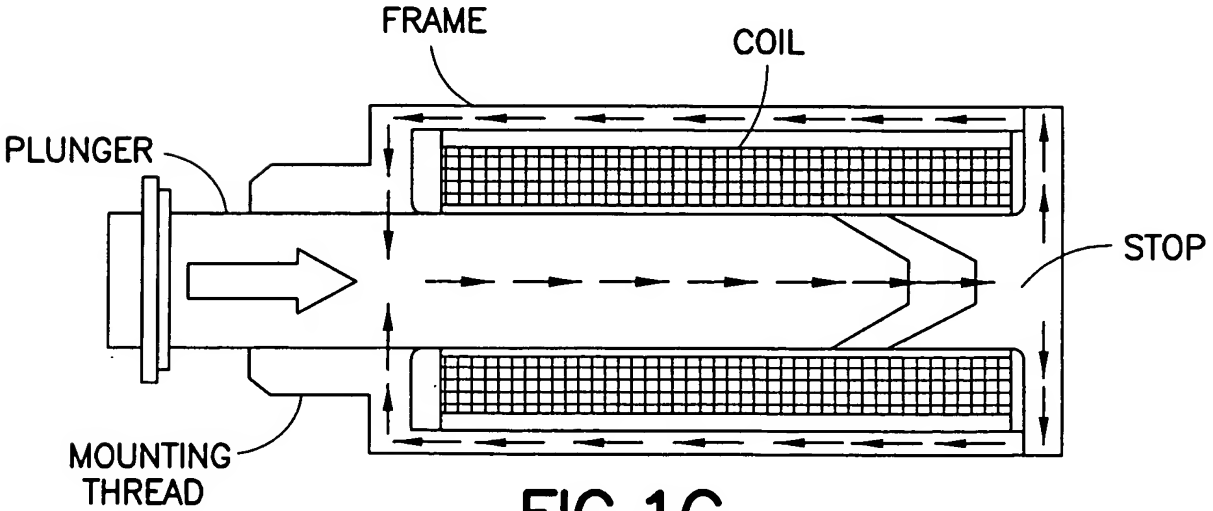


FIG. 1C

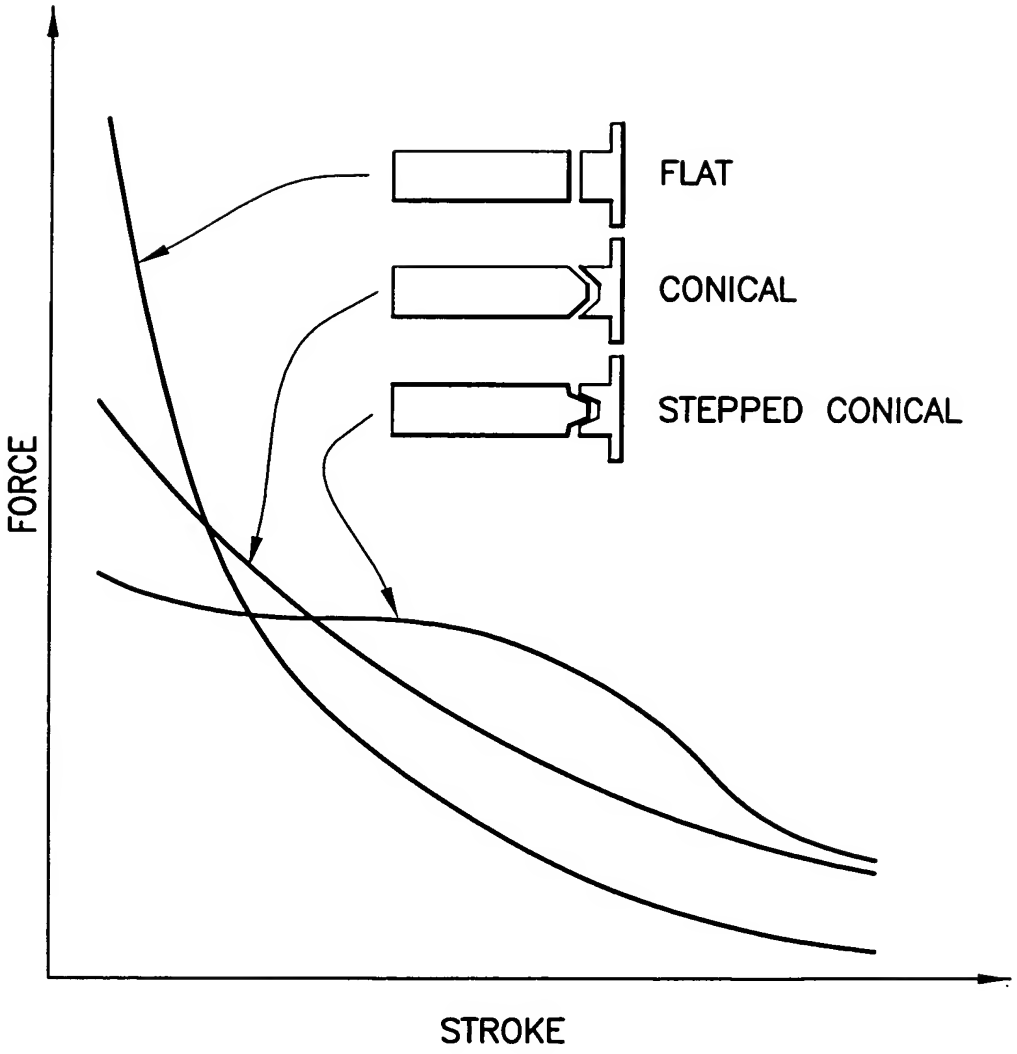
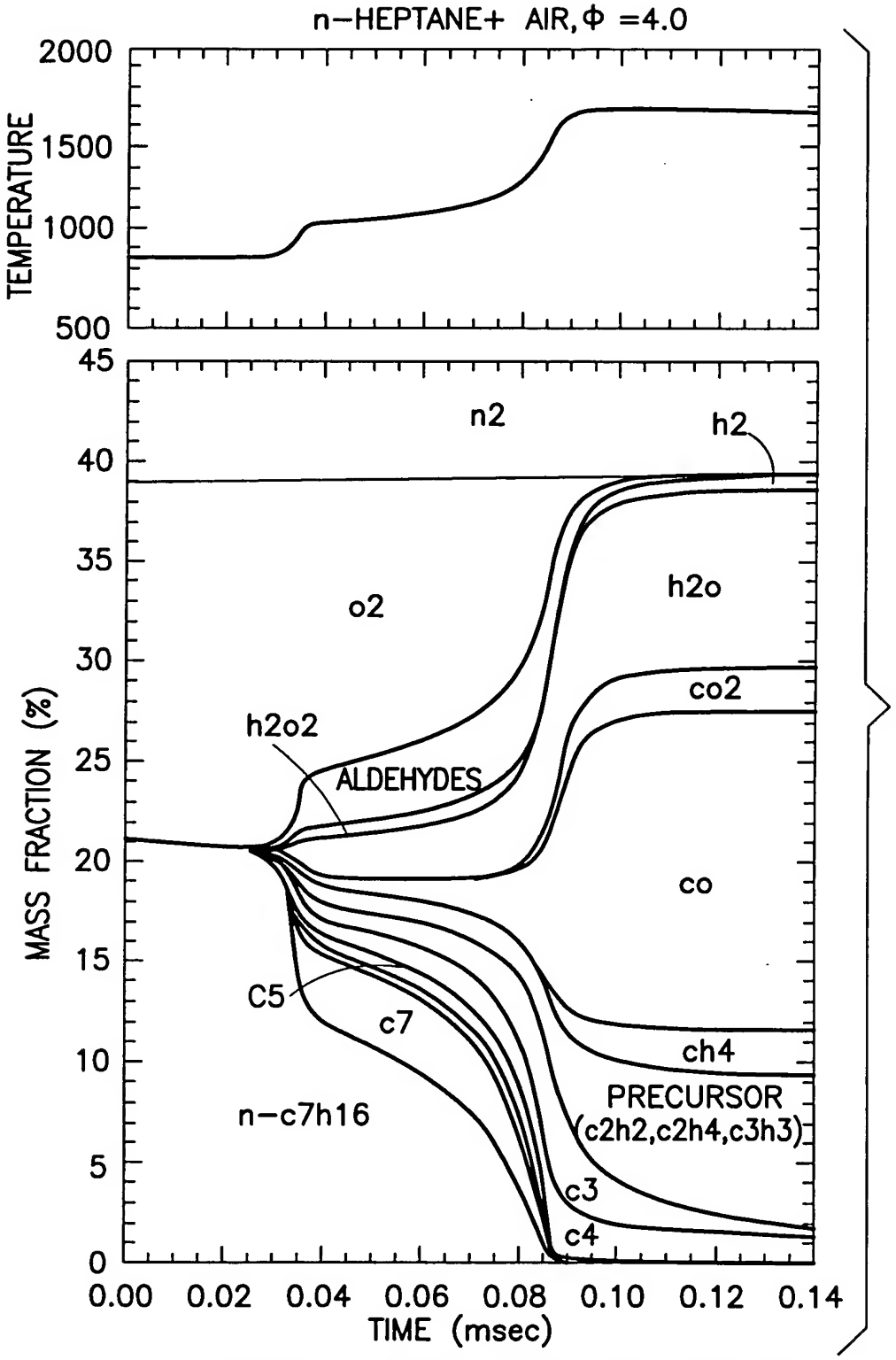


FIG.2



NORMAL HEPTANE REACTIONS STARTING AT 900 °K AND 83 BAR

FIG.3

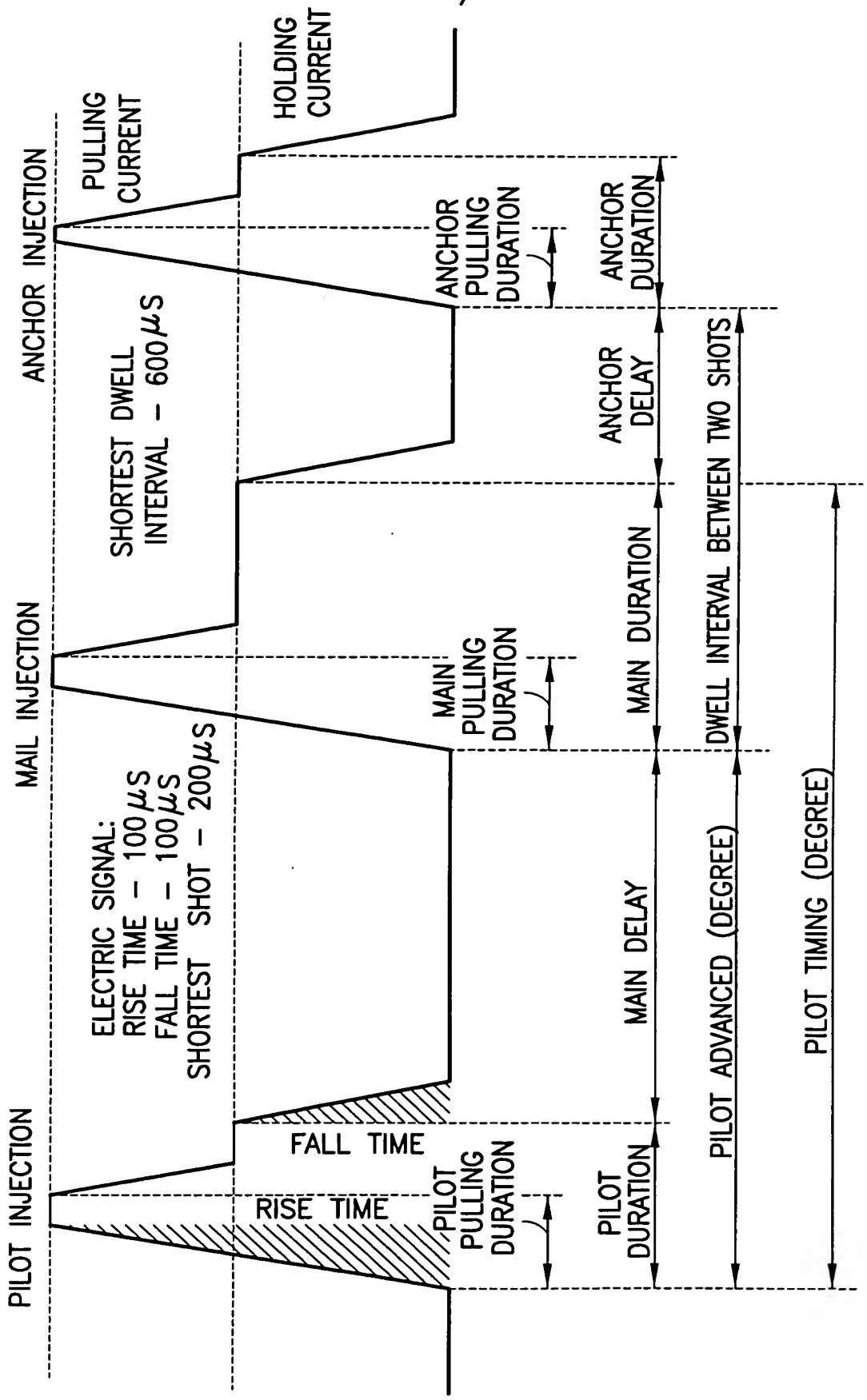

PILOT INJECTION
MAIL INJECTION
ANCHOR INJECTION
ELECTRIC SIGNAL:
RISE TIME - 100μS
FALL TIME - 100μS
SHORTEST SHOT - 200μS
SHORTEST DWELL
INTERVAL - 600μS
PULLING
CURRENT
HOLDING
CURRENT
RISE TIME
FALL TIME
PILOT
PULLING
DURATION
MAIN
PULLING
DURATION
ANCHOR
PULLING
DURATION
PILOT
DURATION
MAIN DELAY
MAIN DURATION
ANCHOR
DELAY
ANCHOR
DURATION
PILOT ADVANCED (DEGREE)
DWELL INTERVAL BETWEEN TWO SHOTS
PILOT TIMING (DEGREE)

FIG.4

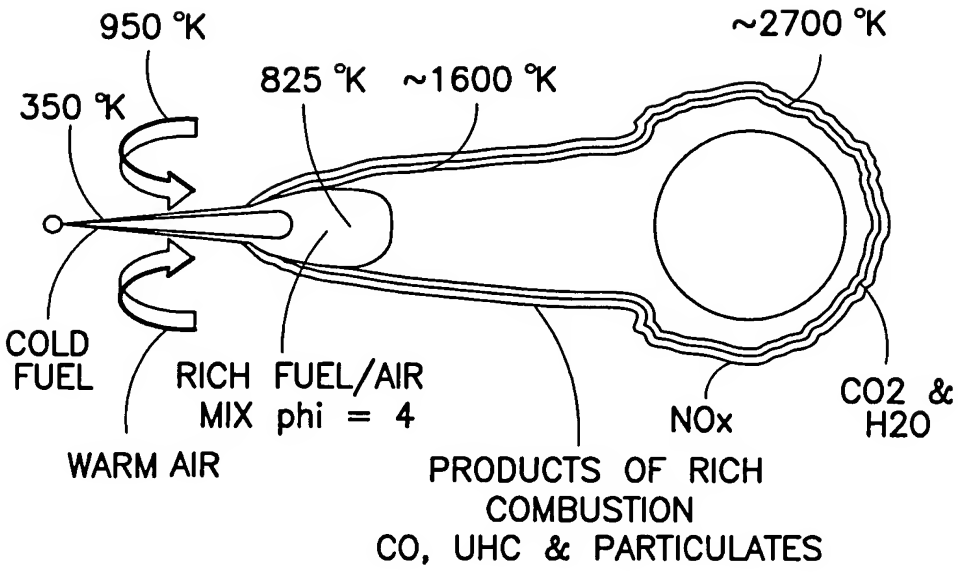

TEMPERATURES
950 °K
350 °K
825 °K
~1600 °K
~2700 °K
COLD FUEL
WARM AIR
RICH FUEL/AIR MIX phi = 4
PRODUCTS OF RICH COMBUSTION
CO, UHC & PARTICULATES
NOx
CO2 & H2O
CHEMISTRY
SUMMARY OF FUEL BURNING PROCESSES

FIG.5

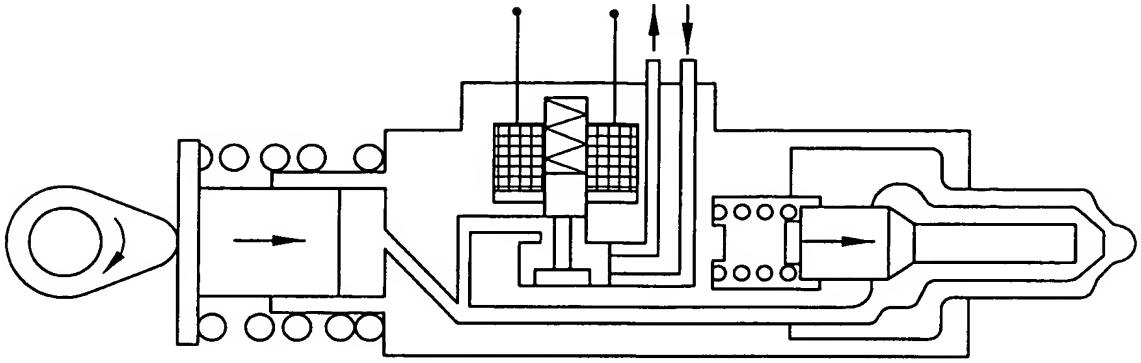


FIG.6D

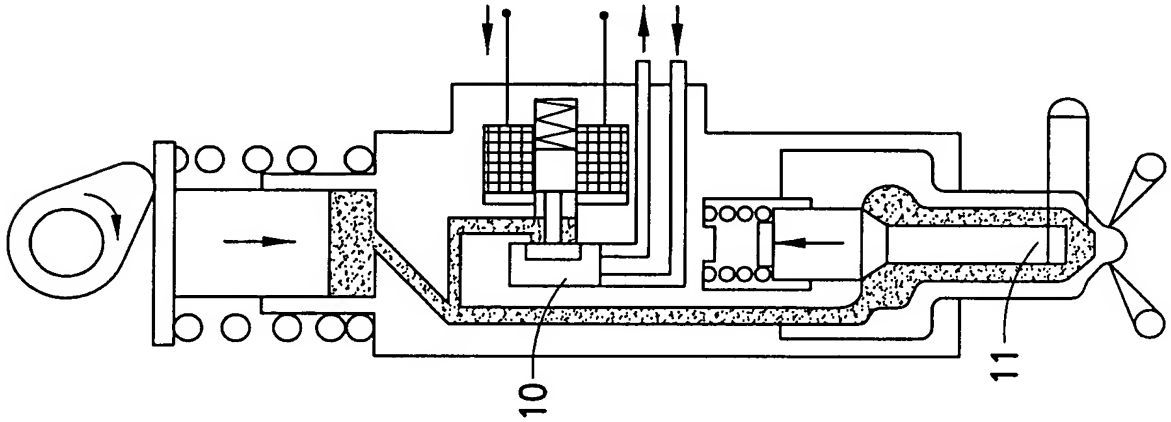


FIG.6C

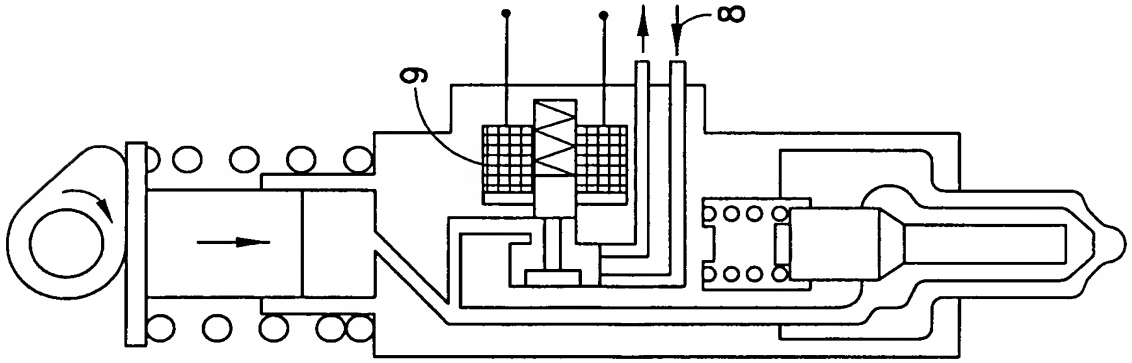


FIG.6B

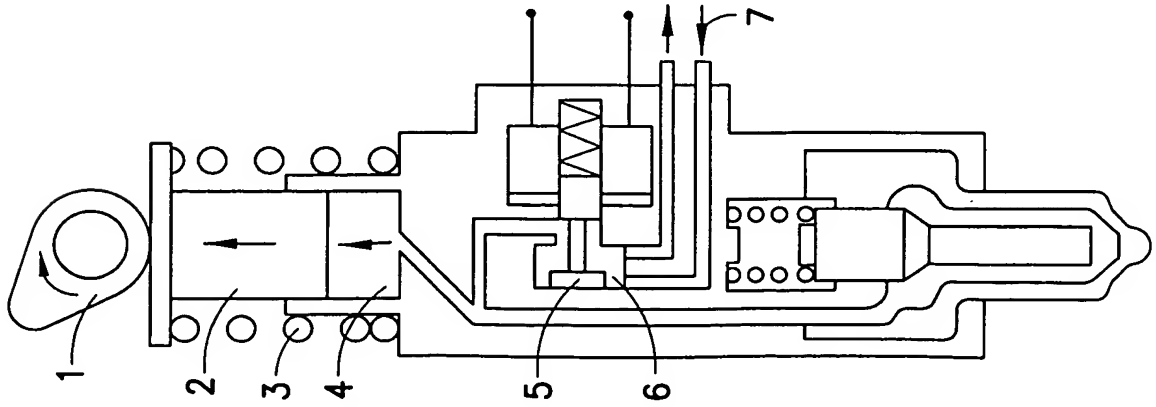


FIG.6A

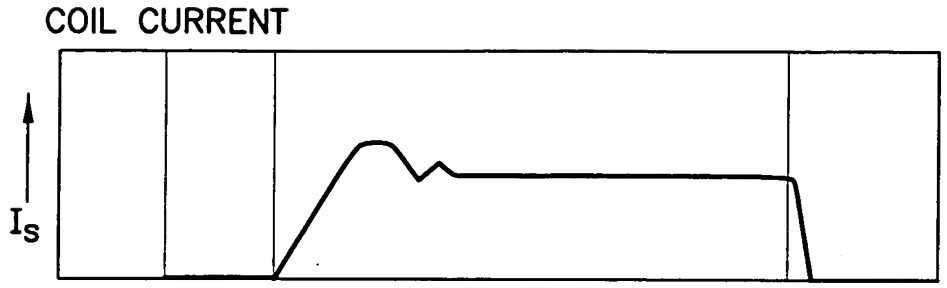


FIG.7A

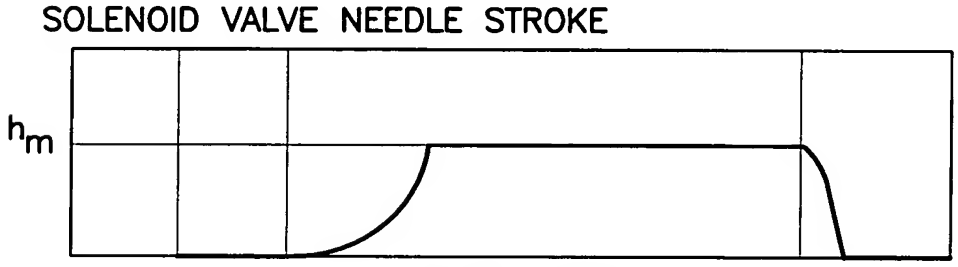


FIG.7B

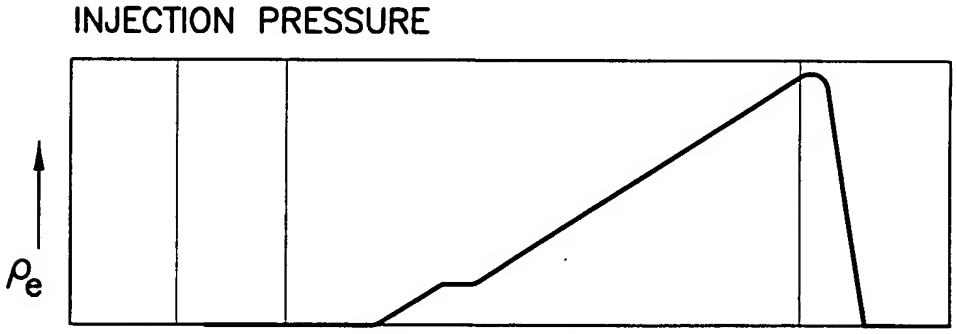


FIG.7C

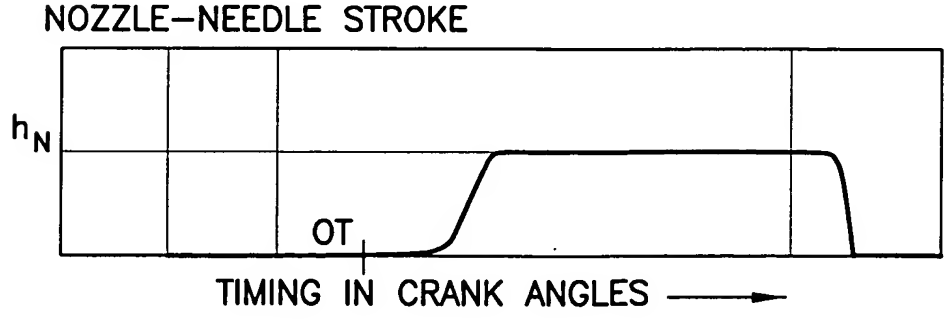


FIG.7D

WAVE FORM DIAGRAM: OPERATION OF THE FUEL INJECTION NOZZLE

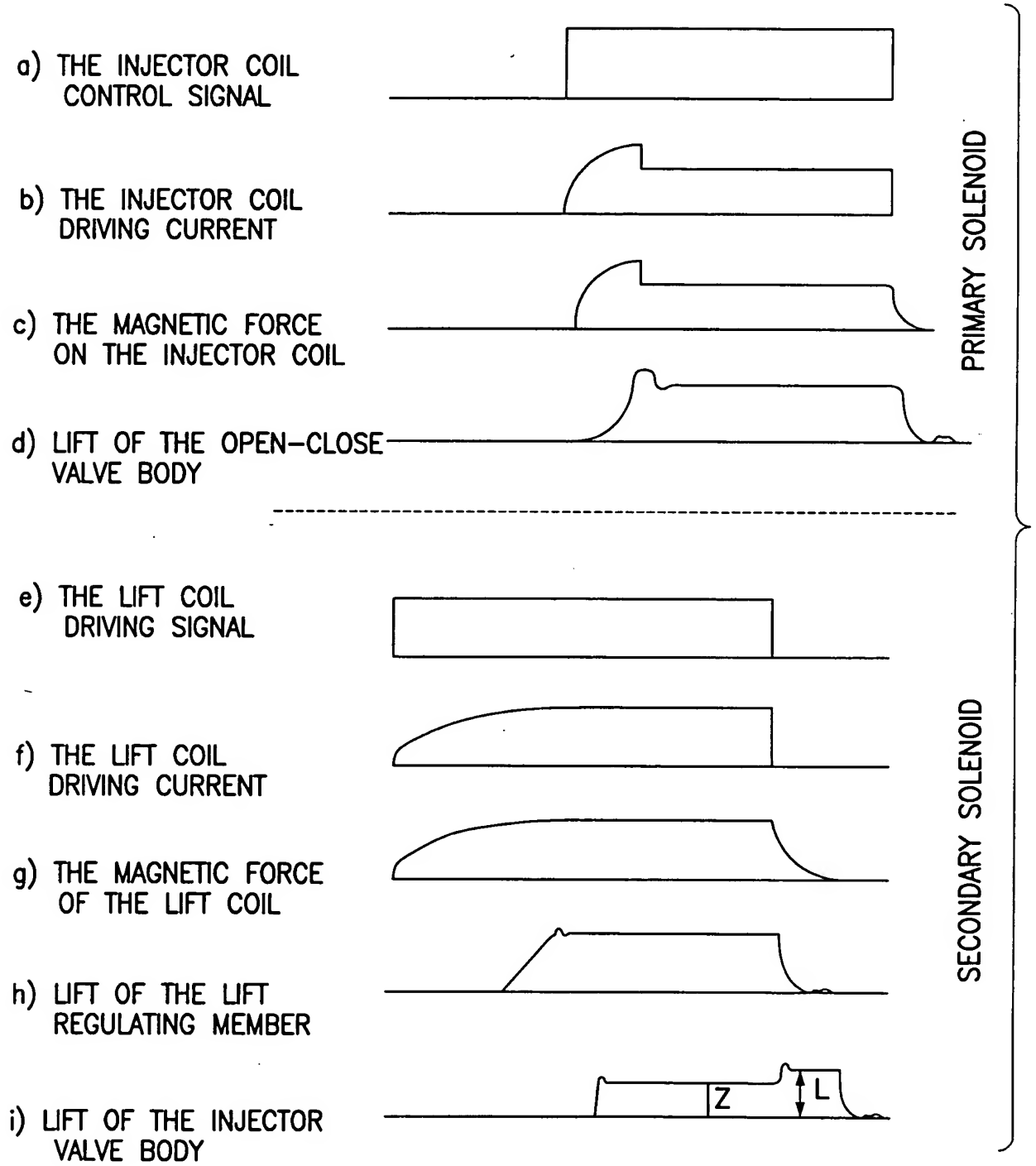


FIG.8

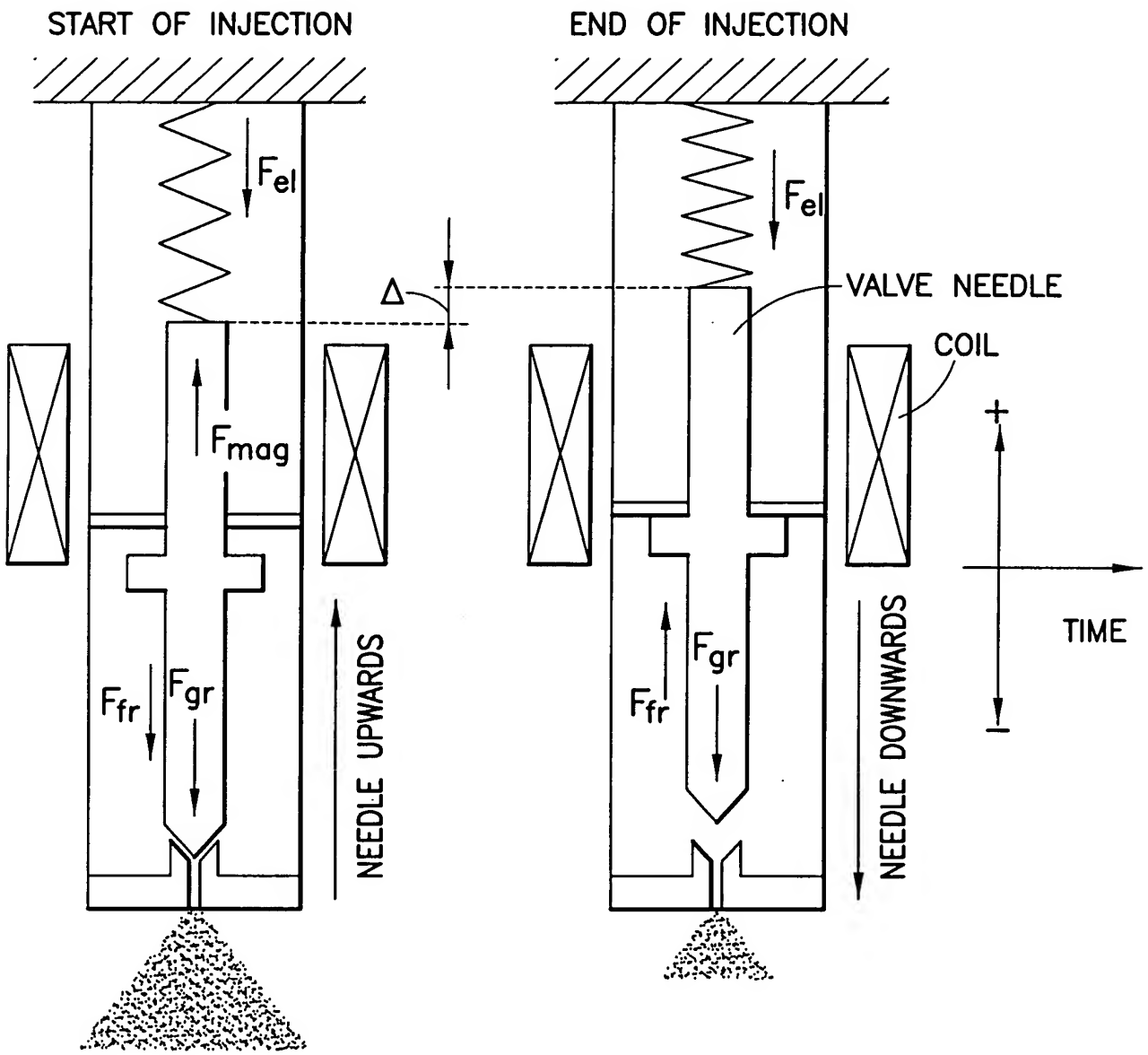

START OF INJECTION
END OF INJECTION
F_{el}
F_{el}
Δ
VALVE NEEDLE
COIL
F_{mag}
F_{fr}
F_{gr}
F_{fr}
F_{gr}
NEEDLE UPWARDS
NEEDLE DOWNWARDS
+
-
TIME

FIG.9

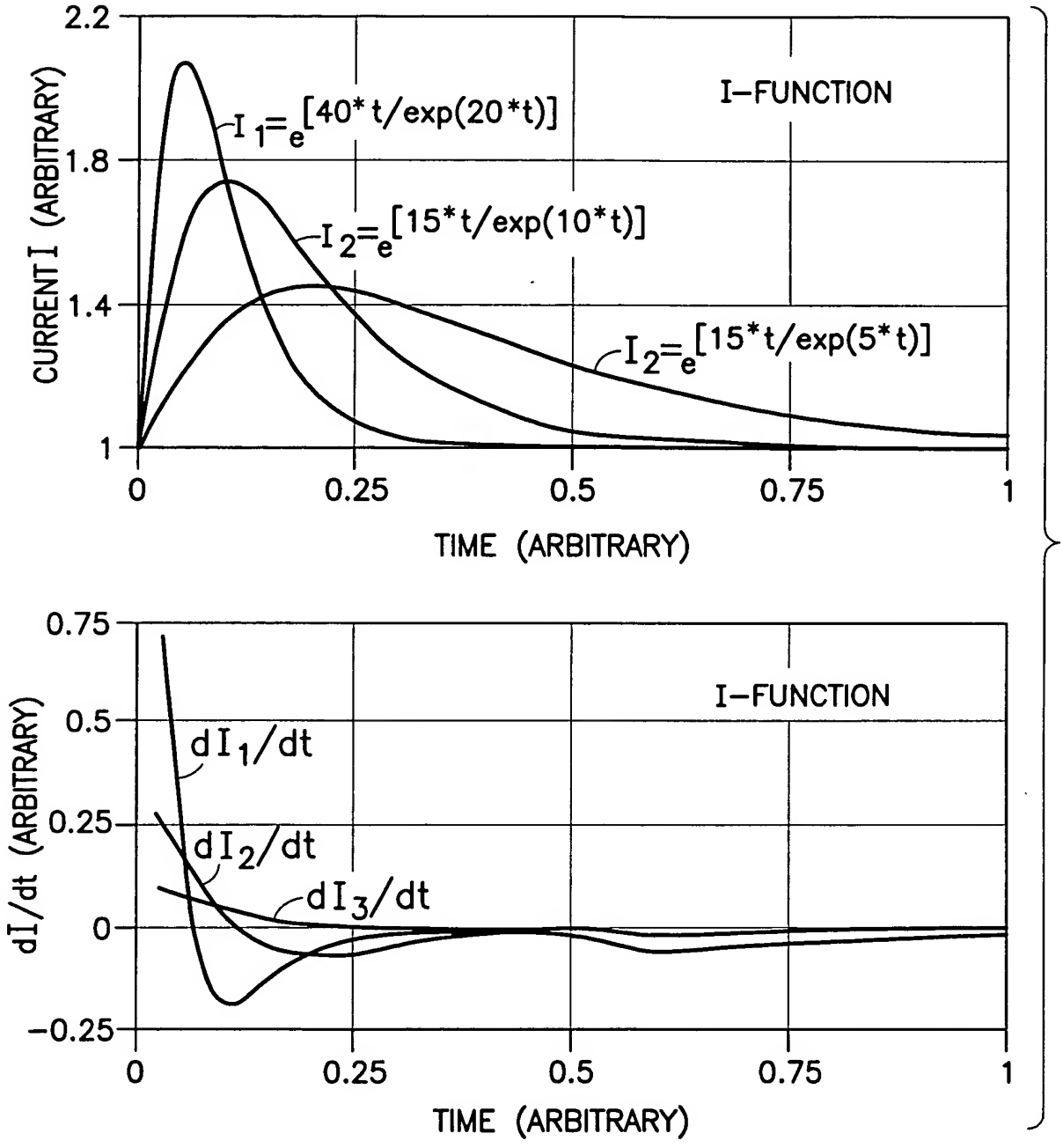

2.2
1.8
1.4
1
CURRENT I (ARBITRARY)
I-FUNCTION
$I_1=_e[40*t/\exp(20*t)]$
$I_2=_e[15*t/\exp(10*t)]$
$I_2=_e[15*t/\exp(5*t)]$
0
0.25
0.5
0.75
1
TIME (ARBITRARY)
0.75
0.5
0.25
0
-0.25
dI/dt (ARBITRARY)
I-FUNCTION
dI_1/dt
dI_2/dt
dI_3/dt
0
0.25
0.5
0.75
1
TIME (ARBITRARY)

FIG.10

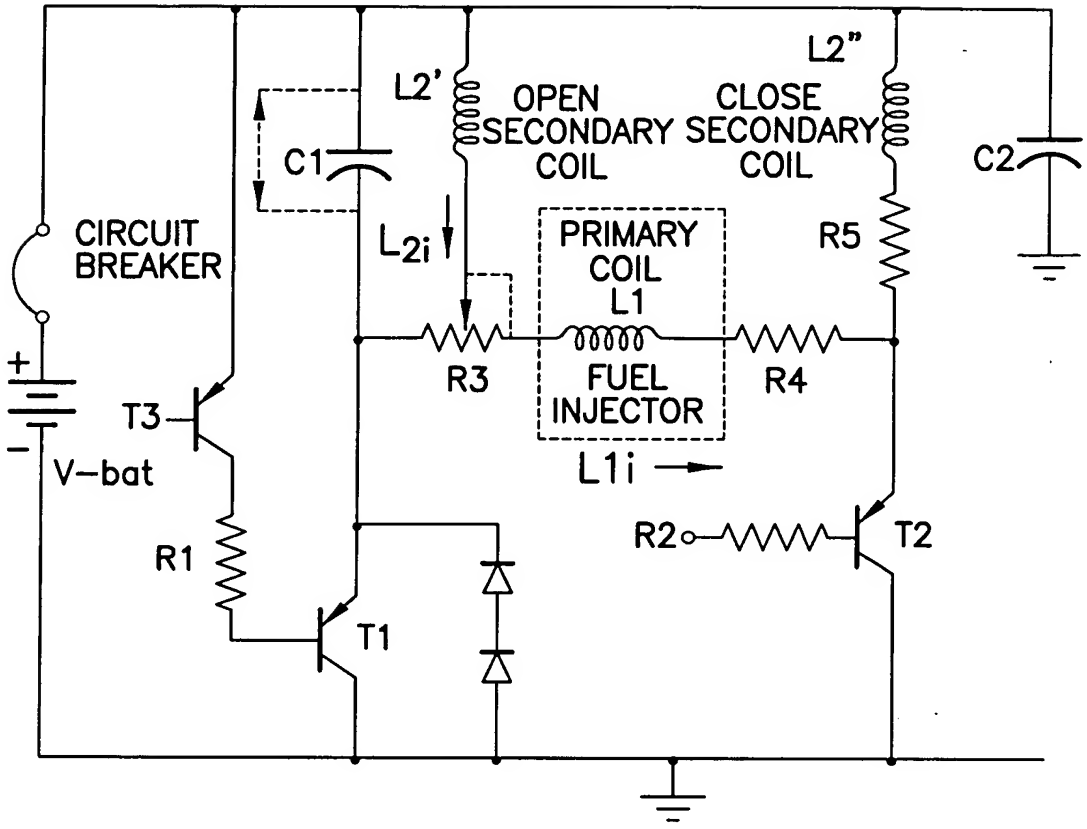


FIG.11A

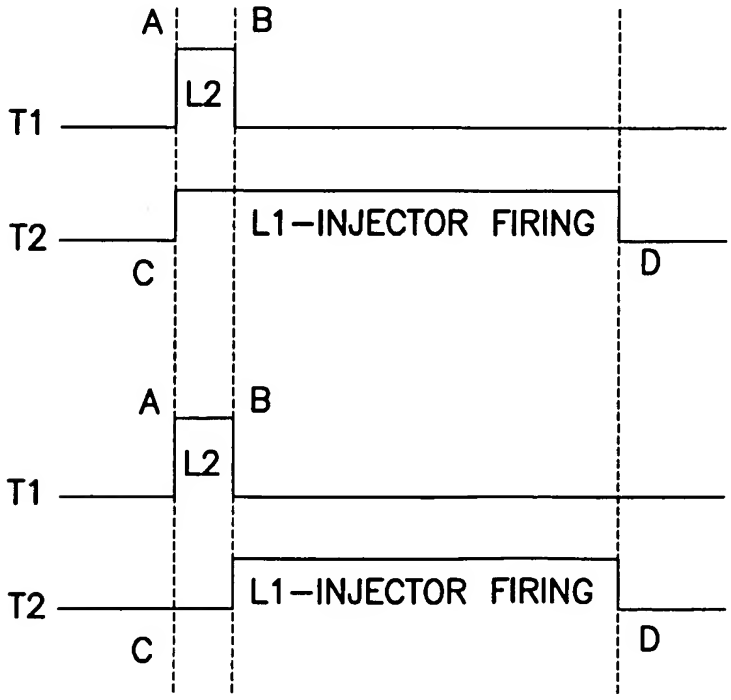


FIG.11B

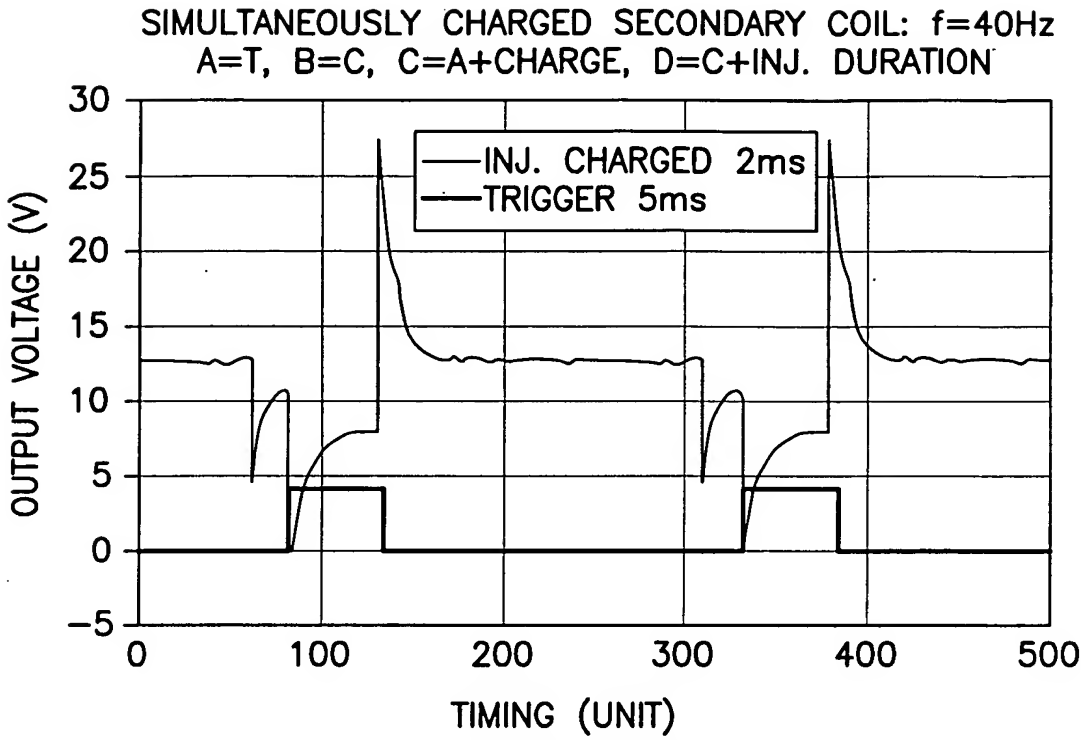


FIG.12A

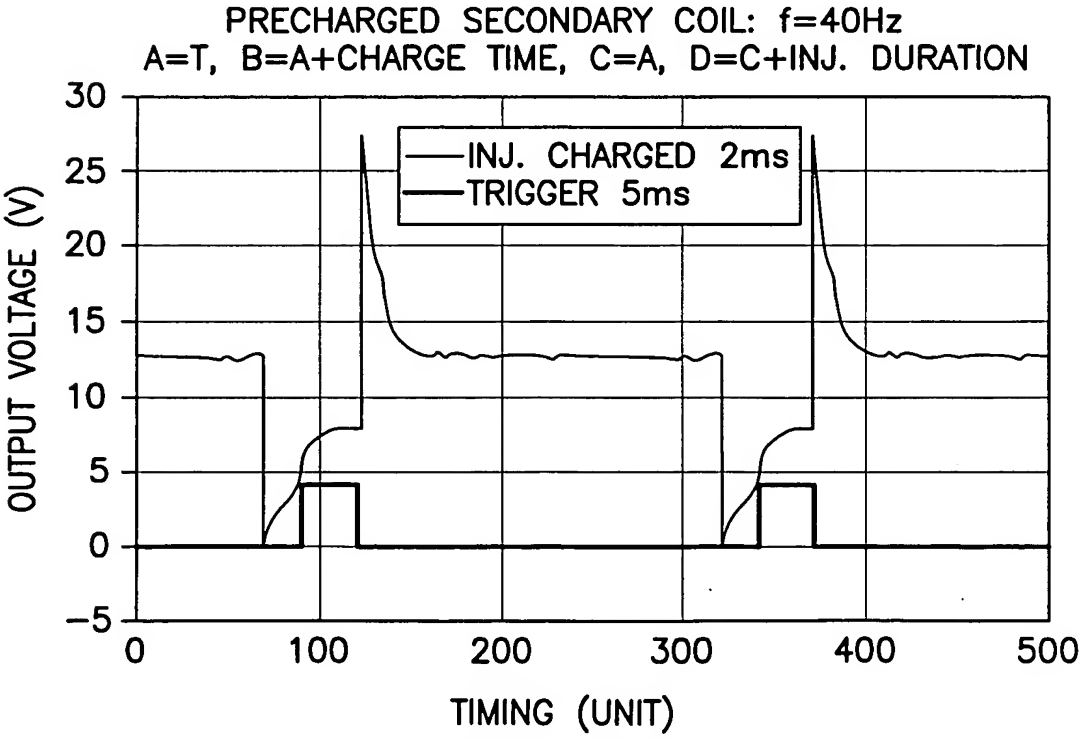


FIG.12B

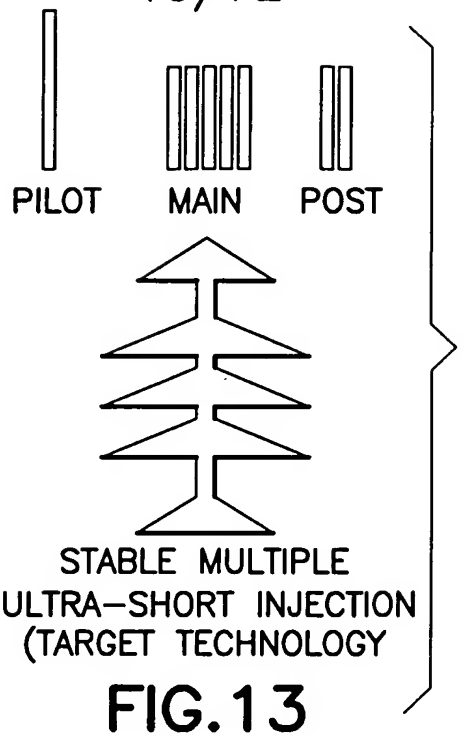

PILOT
MAIN
POST
STABLE MULTIPLE
ULTRA–SHORT INJECTION
(TARGET TECHNOLOGY

FIG.13

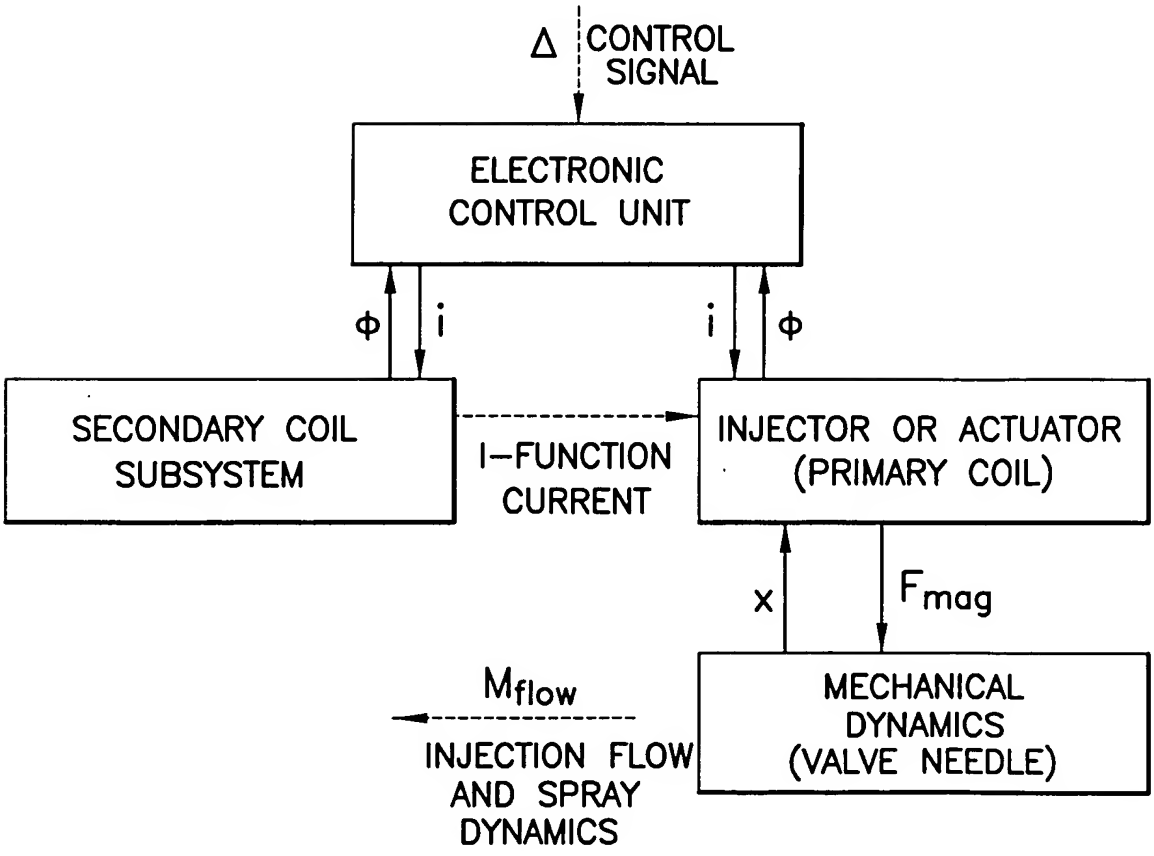

Δ
CONTROL
SIGNAL
ELECTRONIC
CONTROL UNIT
Φ
i
i
Φ
SECONDARY COIL
SUBSYSTEM
I–FUNCTION
CURRENT
INJECTOR OR ACTUATOR
(PRIMARY COIL)
x
Fmag
Mflow
INJECTION FLOW
AND SPRAY
DYNAMICS
MECHANICAL
DYNAMICS
(VALVE NEEDLE)

FIG.14

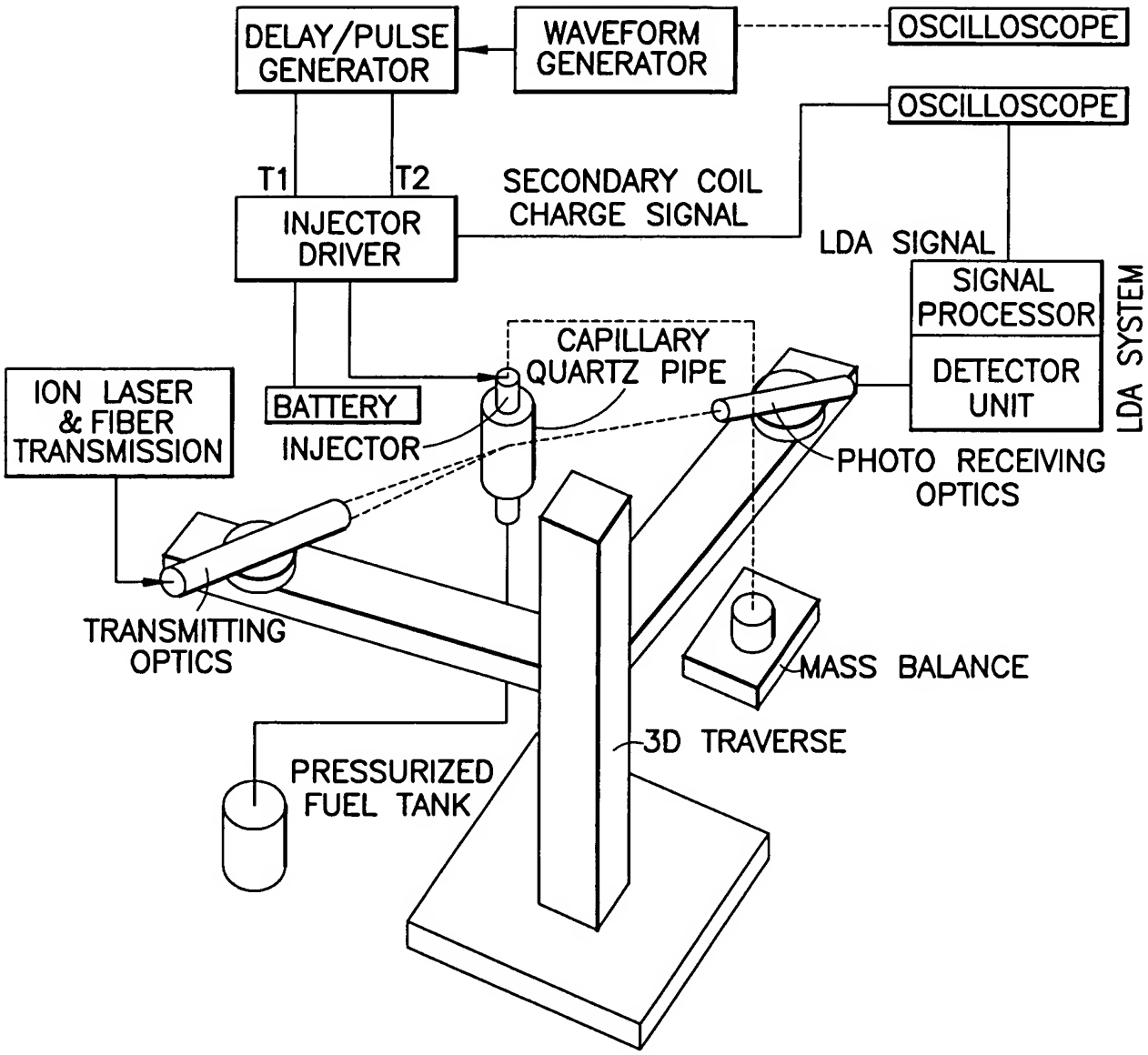

DELAY/PULSE GENERATOR
WAVEFORM GENERATOR
OSCILLOSCOPE
OSCILLOSCOPE
T1
T2
SECONDARY COIL CHARGE SIGNAL
INJECTOR DRIVER
LDA SIGNAL
SIGNAL PROCESSOR
DETECTOR UNIT
LDA SYSTEM
CAPILLARY QUARTZ PIPE
ION LASER & FIBER TRANSMISSION
BATTERY
INJECTOR
PHOTO RECEIVING OPTICS
TRANSMITTING OPTICS
MASS BALANCE
3D TRAVERSE
PRESSURIZED FUEL TANK

FIG.15

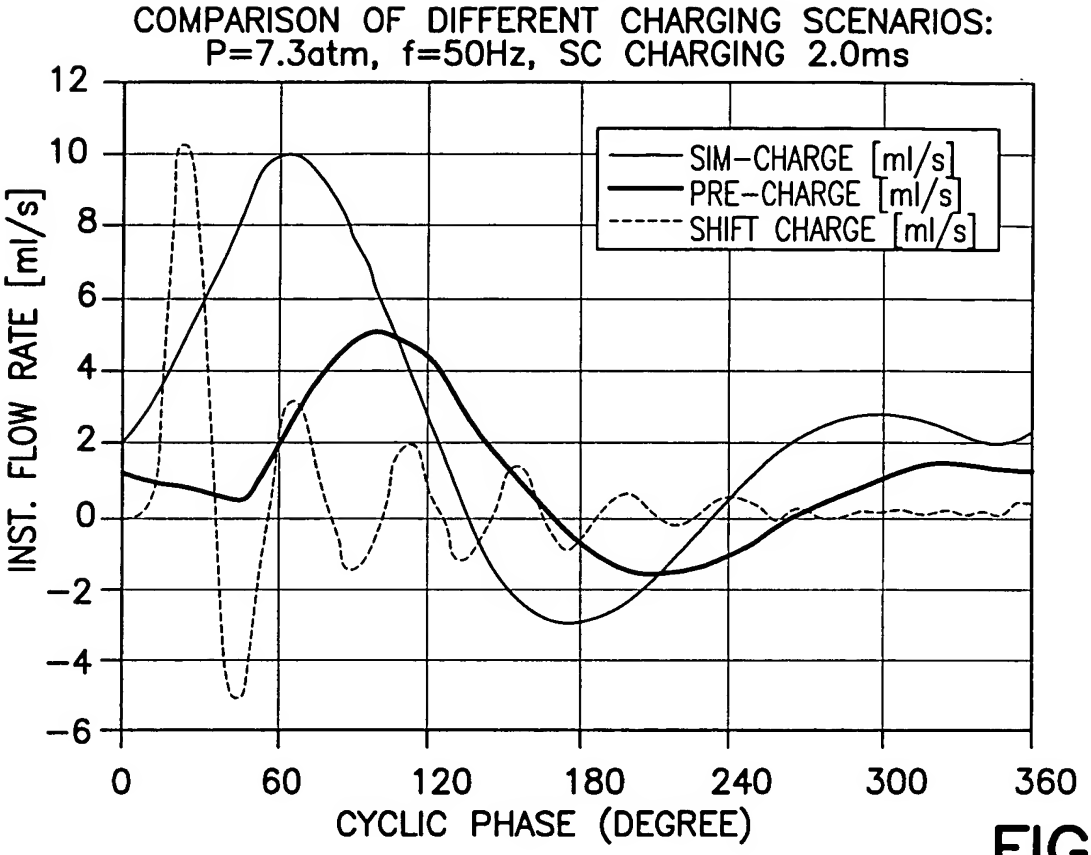


FIG.16A

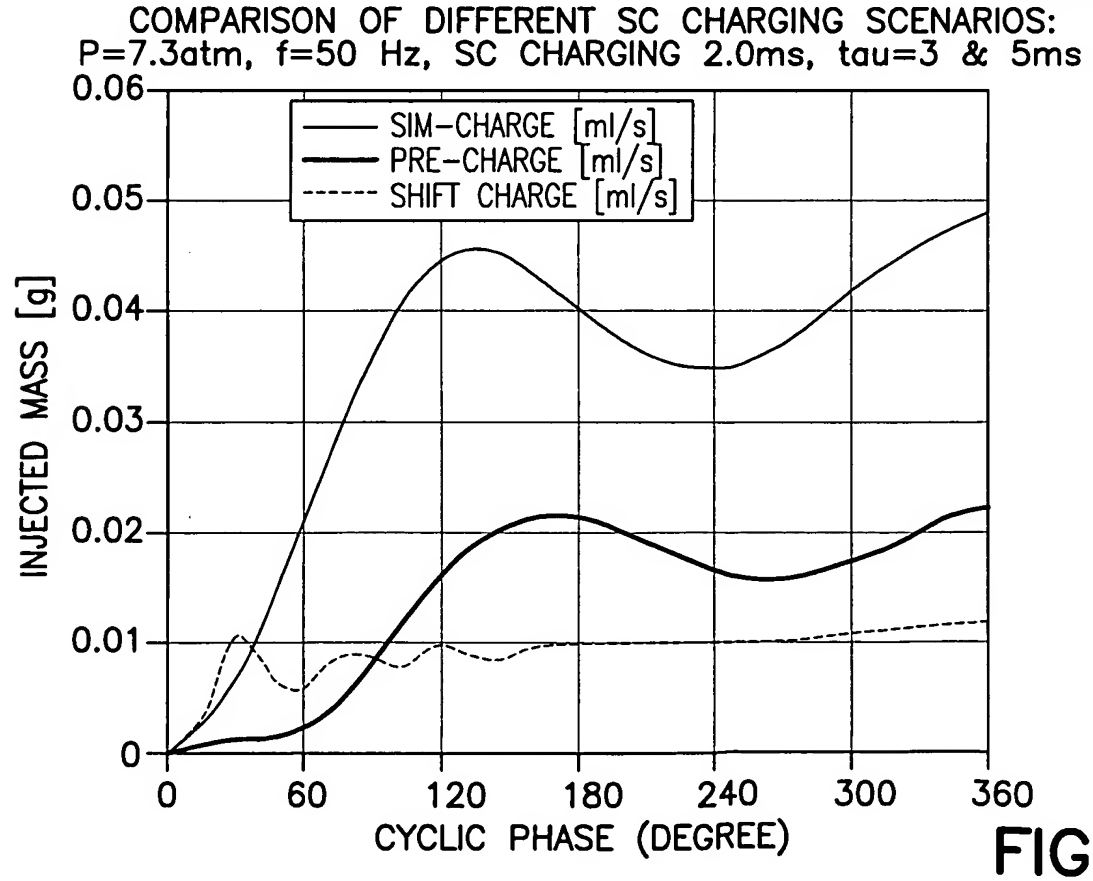


FIG.16B

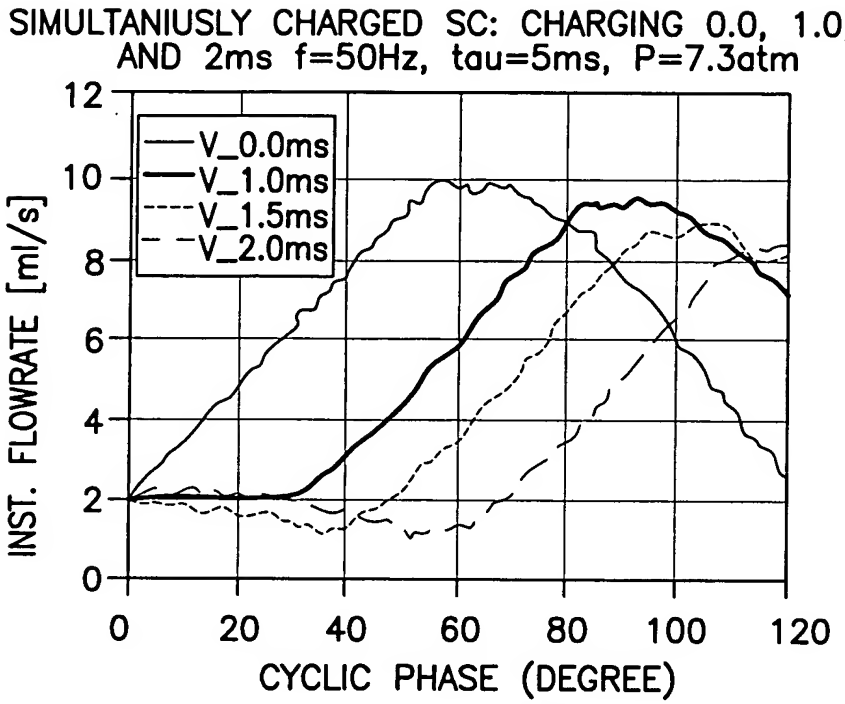


FIG.17A

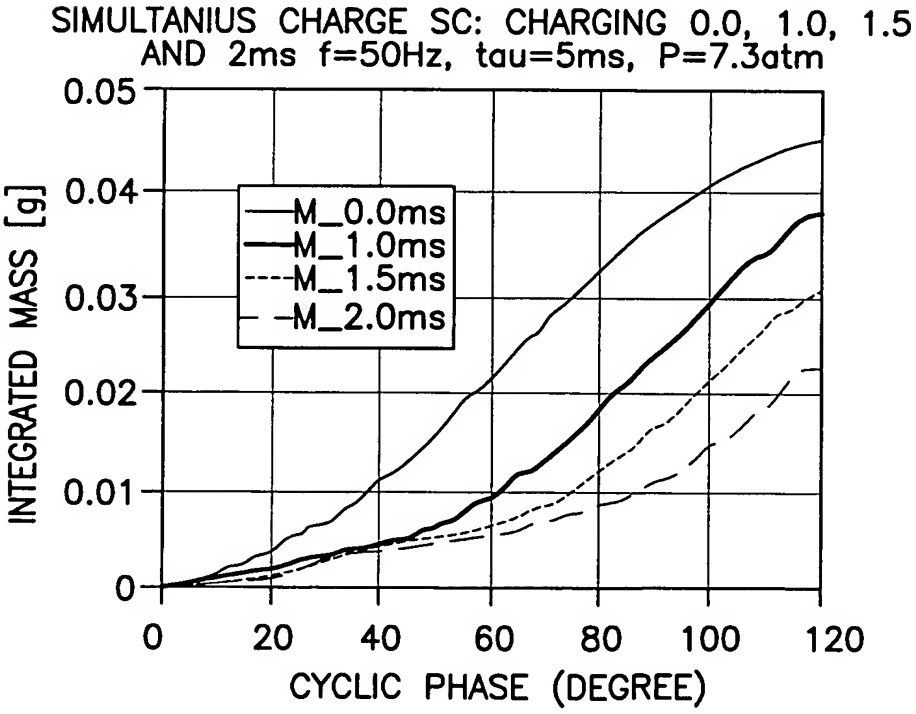


FIG.17B

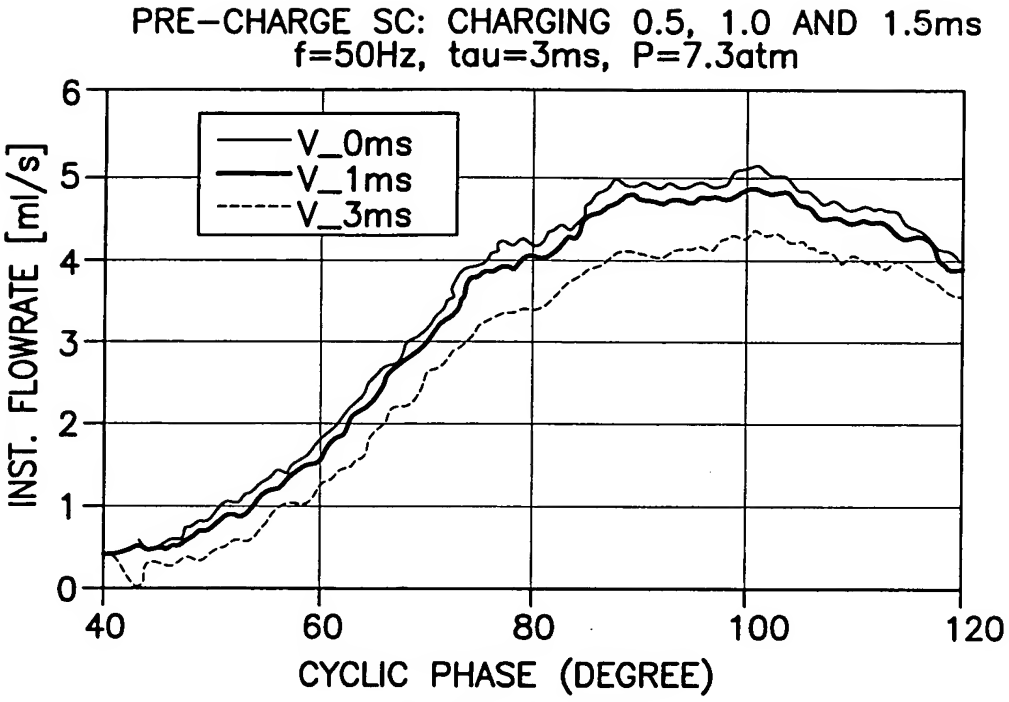


FIG.17C

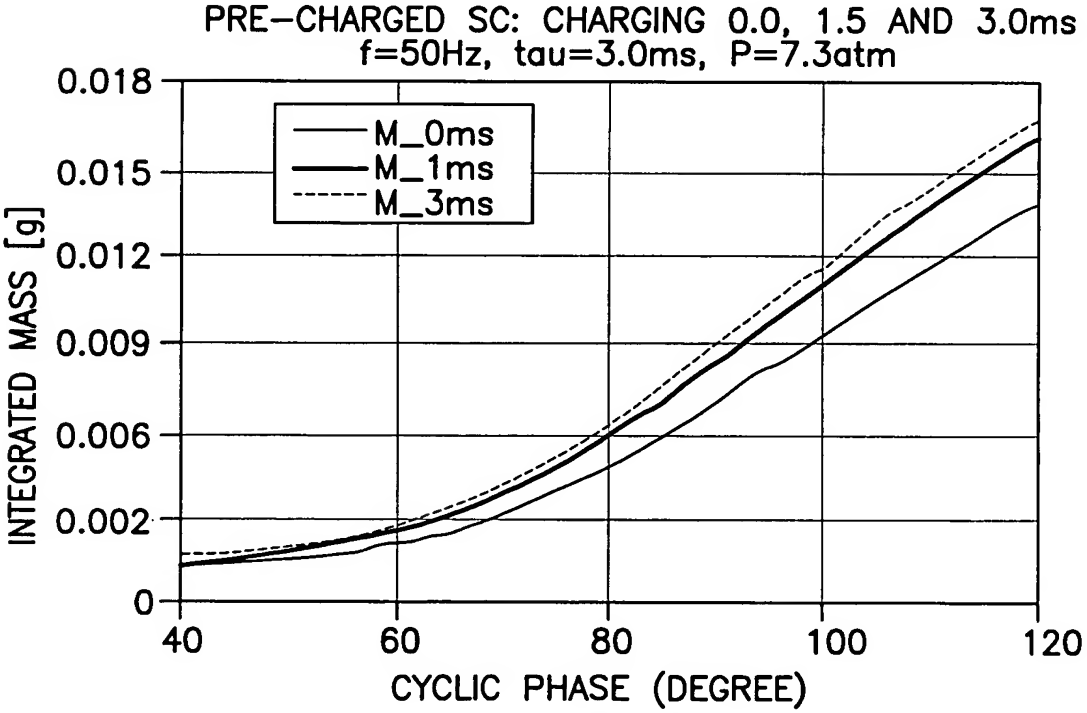


FIG.17D

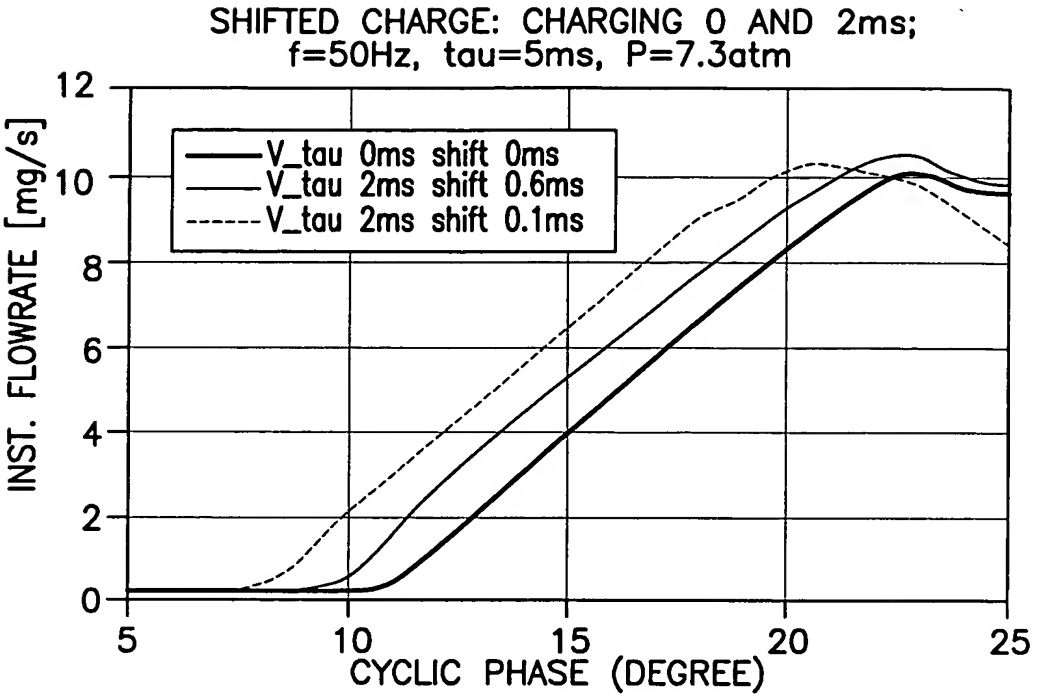


FIG.17E

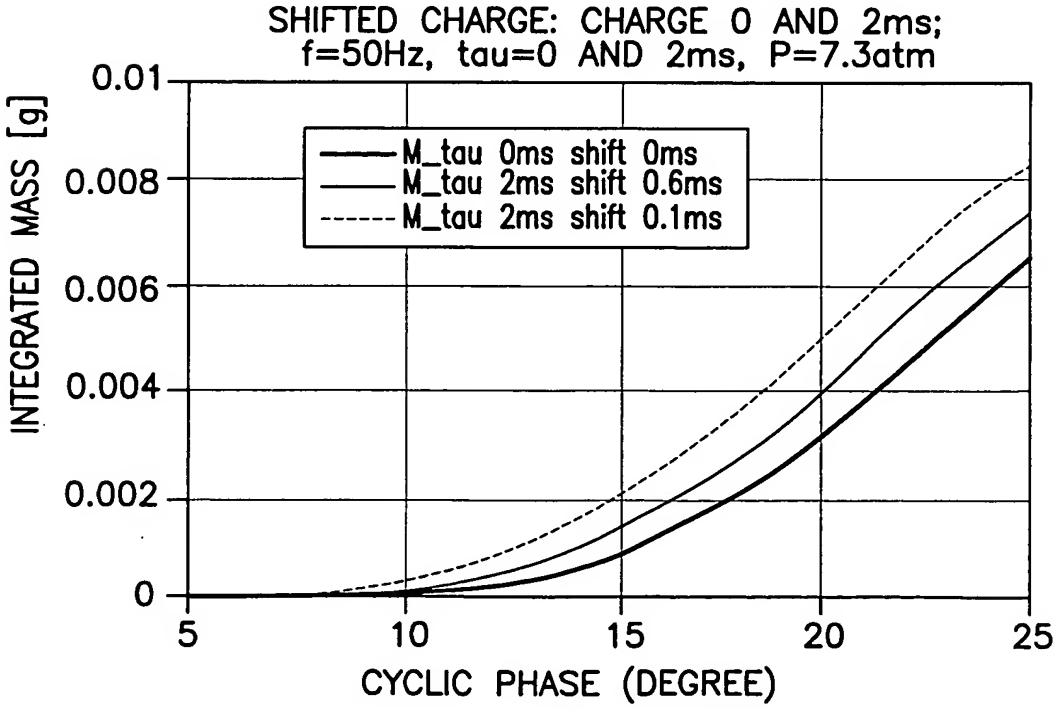


FIG.17F

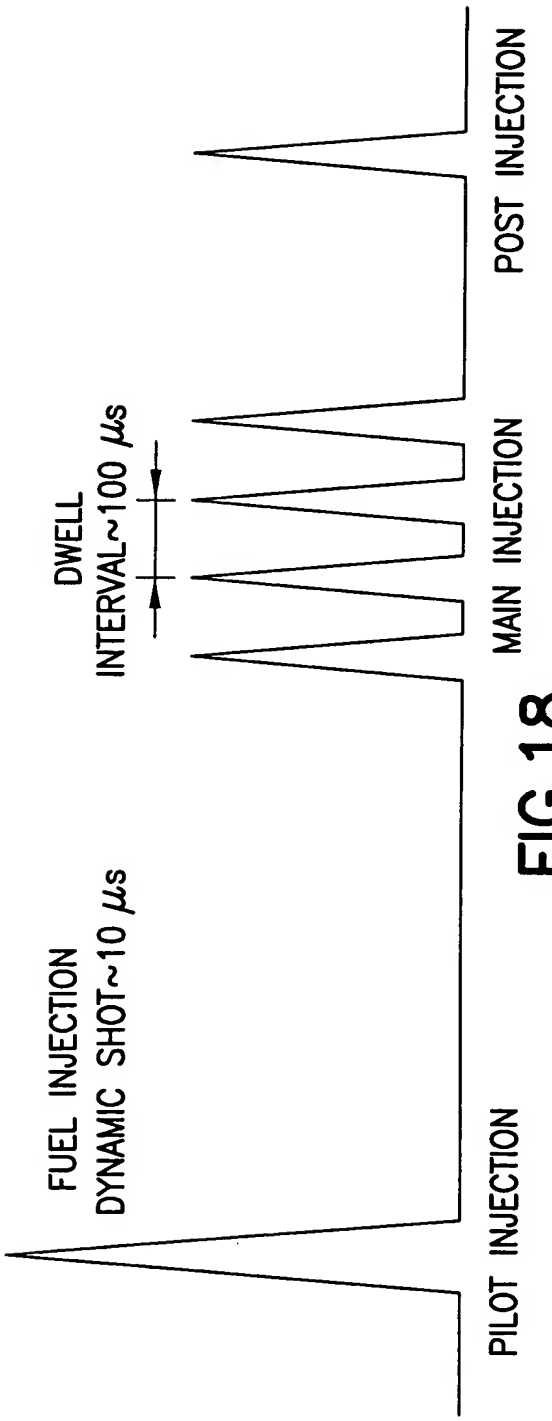

FUEL INJECTION
DYNAMIC SHOT~10 μs
DWELL
INTERVAL~100 μs
PILOT INJECTION
MAIN INJECTION
POST INJECTION

FIG.18

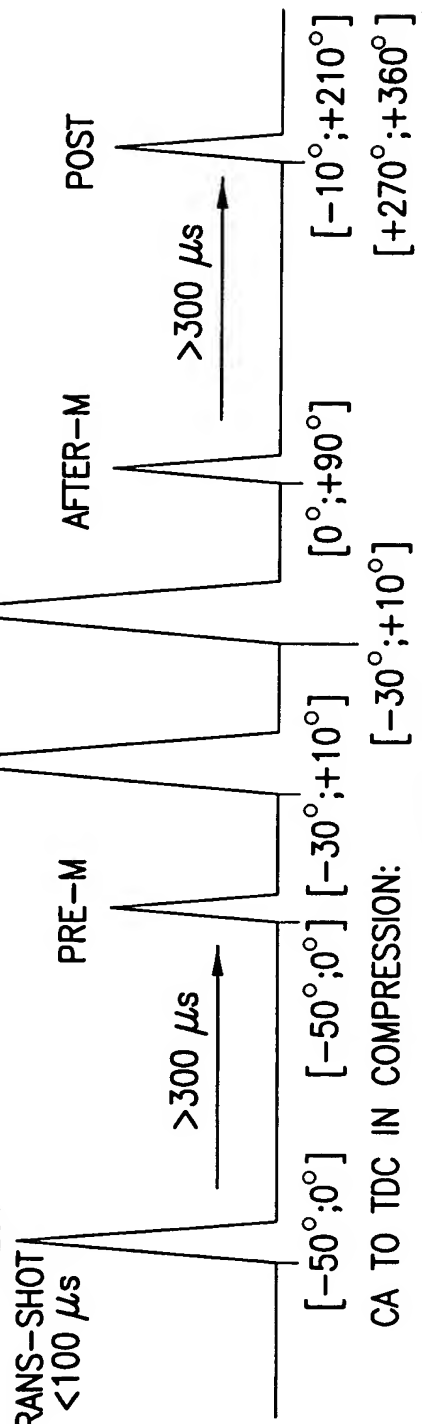

PILOT
TRANS-SHOT
<100 μs
PRE-M
MAIN 1
DWELL
>100 μs
MAIN 2...
AFTER-M
POST
>300 μs
>300 μs
[-50°;0°]
[-50°;0°]
[-30°;+10°]
[0°;+90°]
[-10°;+210°]
CA TO TDC IN COMPRESSION:
[-30°;+10°]
[+270°;+360°]

FIG.19

#	INJECTOR	L_mean μH max	L_mean μH max	R_mean Ω min	R_mean Ω max	TIME L/R μsec AVERAGED	ω21 FREQ R/L kHz AVERAGED	0.5*I²*L/T E_peak W I_p18A	E_hold W I_h12A	4*E_peak W	ω22= w21/2 R/L_22 kHz	T22=T21*2 T=R/L_22 μsec	L_22 μH I_p18A	R_22 Ω R=L/T
BOSCH ENGINE														
1	I	65.73	65.75	0.45	0.45	146	6.85	72.9	4.7	291.6	3.42	292	526	1.80
2	II	76.24	76.35	0.35	0.45	191	5.24	64.8	5.5	259.2	2.62	381	610	1.60
3	III	68.48	68.41	0.35	0.45	171	5.84	64.8	4.9	259.2	2.92	342	548	1.60
3	IV	69.42	69.58	0.35	0.45	174	5.76	64.8	5.0	259.2	2.88	348	556	1.60
ADDIT:														
4	V	79.79	79.85	0.35	0.45	200	5.01	64.8	5.7	259.2	2.51	399	639	1.60
5	VI	84.75	84.84	0.35	0.45	212	4.72	64.8	6.1	259.2	2.36	424	678	1.60
6	VII	79.69	79.69	0.35	0.45	199	5.02	64.8	5.7	259.2	2.51	398	638	1.60

FIG.20

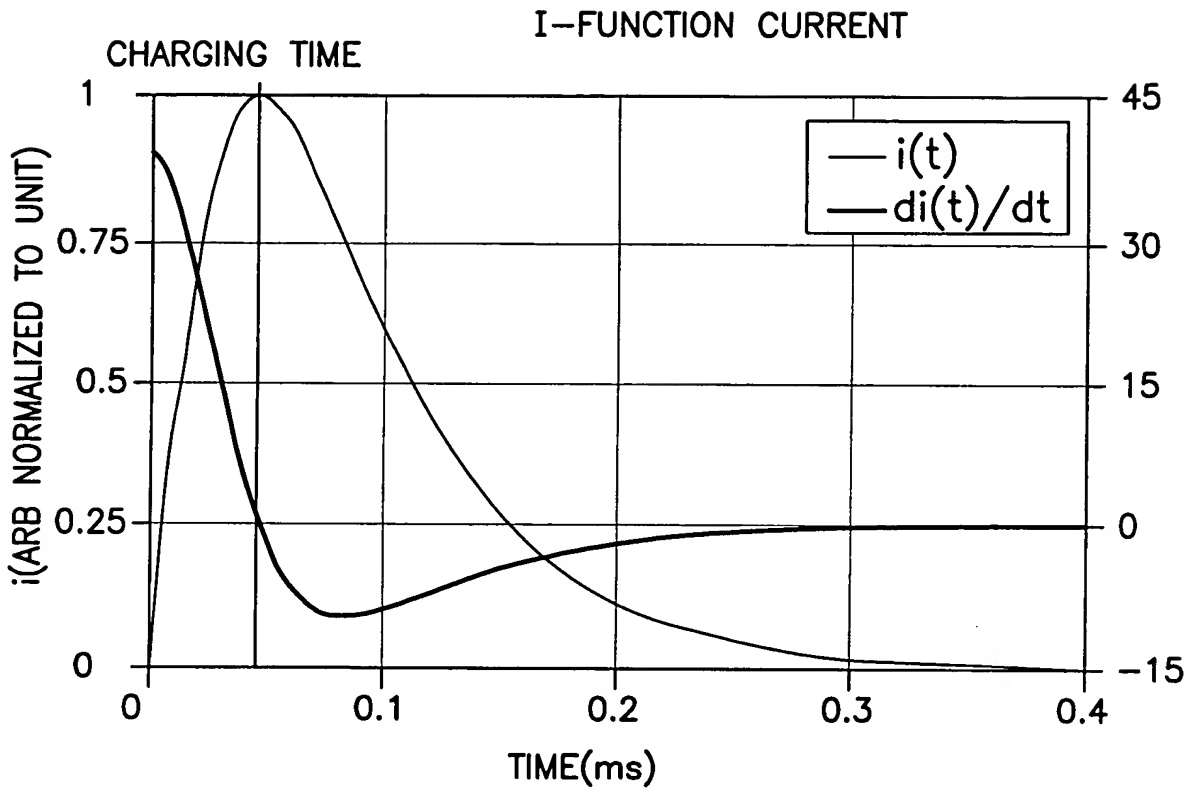

I-FUNCTION CURRENT
CHARGING TIME
i(ARB NORMALIZED TO UNIT)
1
0.75
0.5
0.25
0
45
30
15
0
-15
i(t)
di(t)/dt
0
0.1
0.2
0.3
0.4
TIME(ms)

FIG.21

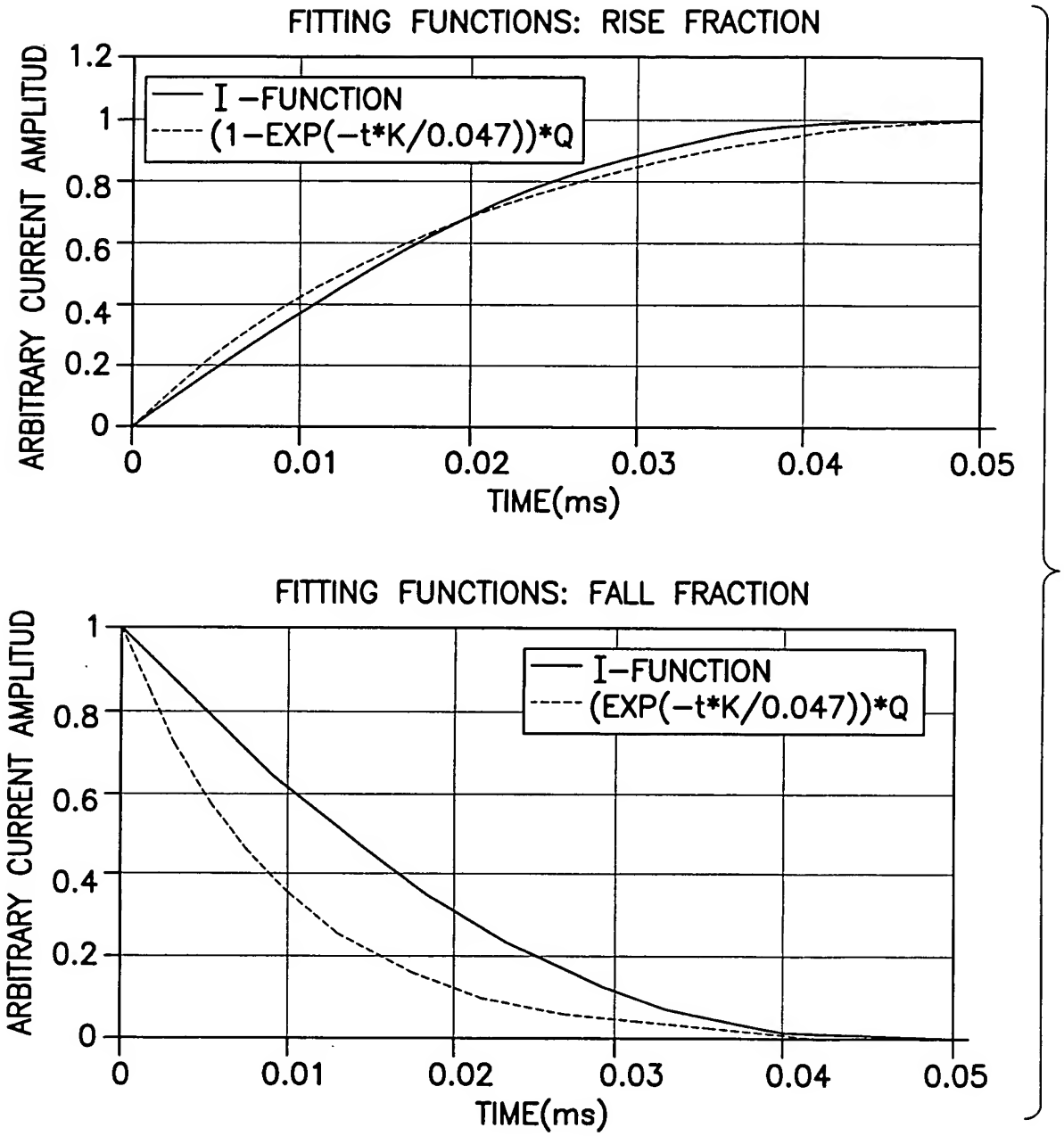

FITTING FUNCTIONS: RISE FRACTION
ARBITRARY CURRENT AMPLITUD
1.2
1
0.8
0.6
0.4
0.2
0
I –FUNCTION
(1–EXP(–t*K/0.047))*Q
0
0.01
0.02
0.03
0.04
0.05
TIME(ms)
FITTING FUNCTIONS: FALL FRACTION
ARBITRARY CURRENT AMPLITUD
1
0.8
0.6
0.4
0.2
0
I–FUNCTION
(EXP(–t*K/0.047))*Q
0
0.01
0.02
0.03
0.04
0.05
TIME(ms)

FIG.22

FIG.23A

No.	PARAMETER	CALCUL FORMULA	DIMENSION	VALUE	CONTROL	DEVICE/UNIT
1	INDUCTANCE	L, MEASURED	μH	#REF!	L/R METER IIB	BOSCH INJECTORI
2	RESISTANCE	R, MEASURED	Ω	#REF!	MUTIMETER	BOSCH INJECTORI
3	T-RESPONCE	L/R	μs	#REF!	HP INFINUM SCOPE 500 MHz, 1GSa/s	BOSCH PROFILE
4	F-RESPONCE	R/L	kHz	#REF!	HP INFINUM SCOPE 500 MHz, 1GSa/s	BOSCH PROFILE
5	CYCLE [Hz] 33.33	CONSIDERED	DEGREE ms pts	360 30.0 16000	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM
6	P INJECTION OFFSET "-X deg BTDC"	CONSIDERED START	DEGREE ms pts	157.5 13.13 7000	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM
7	M INJECTION OFFSET "TDC"	CONSIDERED	DEGREE ms pts	180 15.00 8000	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM

8	P_M INTERVAL	P_off – M_off X BTC	DEGREE μs pts	22.5 1875 1000	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM
9	NORMAL INJECTION "–X deg BTDC"	max 2.2 ms	DEGREE μs pts	26.4 2200 1173	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM
10	P_DURATION= M_DURATION	CONSIDERED	DEGREE μs pts	7.2 600 320	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM
11	P_M_dwell	(P_off–M_off)–P_dur	DEGREE μs pts	15 1275 680	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	SOLENOID INJECTOR PROGRAM
12	TOTAL INJECTION DURATION	P_dur+dwell+M_d_off	DEGREE μs pts	30 2475 1320	HP/AGILENT 33120A 15 MHz WAVEGENERATOR	INJECTOR SOLENOID PROGRAM

FIG.23B

FIG.23A

FIG.23B

FIG.23

SCALES	I[A]	2.0	t[ms]	0.200
	L[mm]	9.8	L[mm]	14.1
	I/L[A/mm]	0.204t/L[ms/mm]		0.01418

FIRST SHOT [us]	600	POINTS	320
SECOND SHOT [us]	600	POINTS	320
DWELL INTERVAL [us]	1275	POINTS	680

PROFILE MI_33_2x600_1275_SC	PHASE	τ_lin[mm]	I_lin[mm]	τ_abs[ms]
τ_off[pts]				
7000	A	0.0	0.0	0.000
157.5°	B	I-FUNCTION	FIRST PEACK	0.175
FIRST SHOT	C	3.6	56.2	0.051
	D	CALCULATION	56.0	0.280
	E	I-FUNCTION	0.0	0.094
			TOTAL	0.600
	CD_osc	4.5	2.8	0.128
τ_off[pts]				
8000	A	0.0	0.0	0.000
180°	B	I-FUNCTION	FIRST PEACK	0.175
SECOND SHOT	C	3.6	56.2	0.051
	D	CALCULATION	56.0	0.280
	E	I-FUNCTION	0.0	0.094
	CD_osc	4.5	2.8	0.128

FIG.24A

T[pts]	16000
V_arb[−]	1
R[Ohm]	0.45
T[ms]	30.0

FIG.24A	FIG.24B

FIG.24

TOTAL pts 320 NUMBER OF SINE CYCLE 5
exp_rise 9.36
exp_fall 9.60

I_abs[A]	pts[−]	I_arb[−]	V_abs[V]	Δτ_pts[−]	ΔI_arb[−]	ΔV_abs[V]
0.00	7000	0.000	0.000	0	0.000	0.000
17.80	7093	1.000	8.010	93	1.000	8.010
11.46	7121	0.644	5.159	27	−0.356	−2.851
11.42	7270	0.642	5.141	149	−0.002	−0.018
0.00	7320	0.000	0.000	50	−0.642	−5.141
			TOTAL	320		
0.57	61	0.032	0.257			
0.00	8000	0.000	0.000	0	0.000	0.000
17.80	8093	1.000	8.010	93	1.000	8.010
11.46	8121	0.644	5.159	27	−0.356	−2.851
11.42	8270	0.642	5.141	149	−0.002	−0.018
0.00	8320	0.000	0.000	50	−0.642	−5.141
			TOTAL	320		
0.57	61	0.032	0.257			

FIG.24B

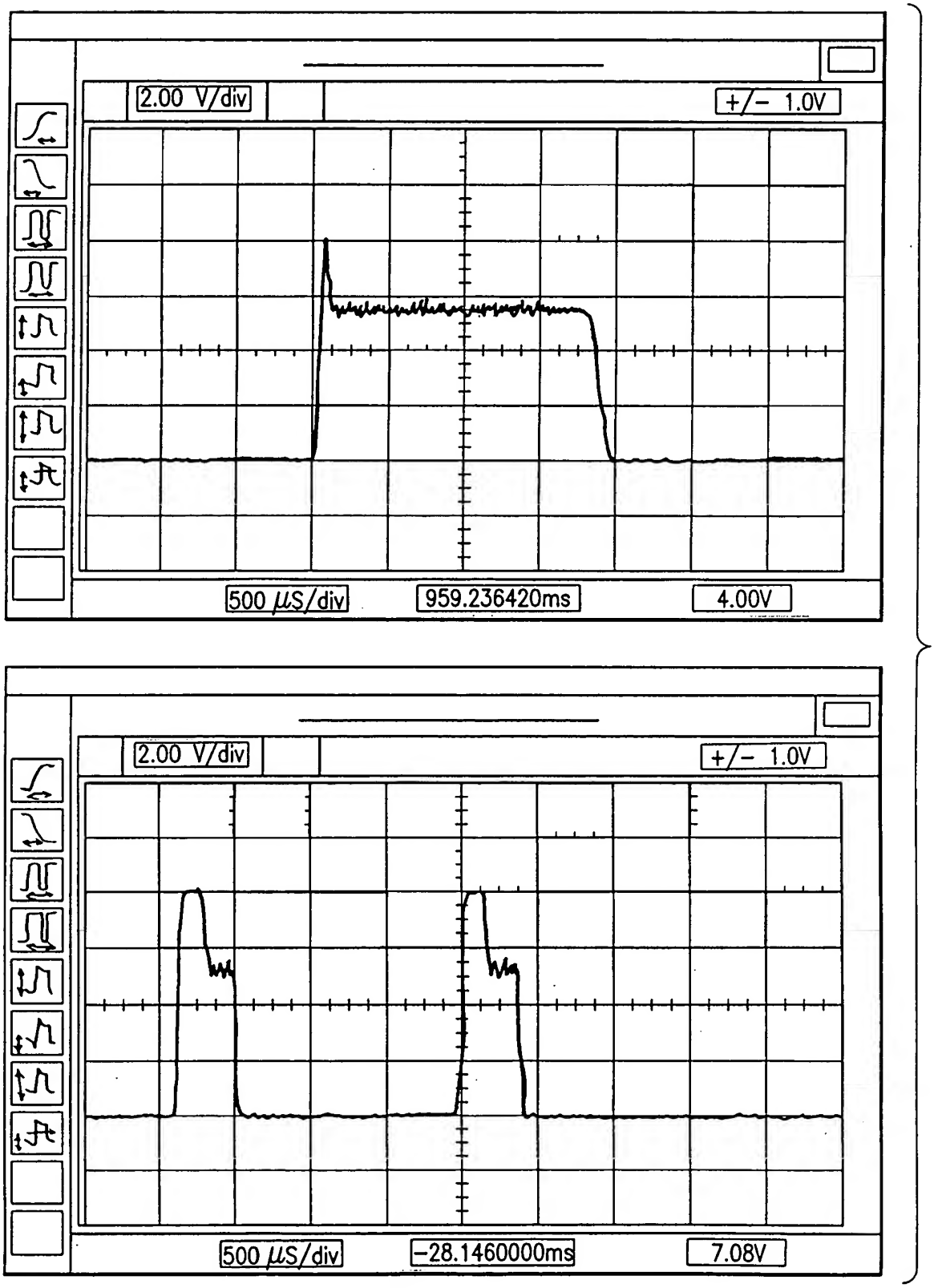

2.00 V/div
+/- 1.0V
500 µS/div
959.236420ms
4.00V
2.00 V/div
+/- 1.0V
500 µS/div
-28.1460000ms
7.08V

FIG.25

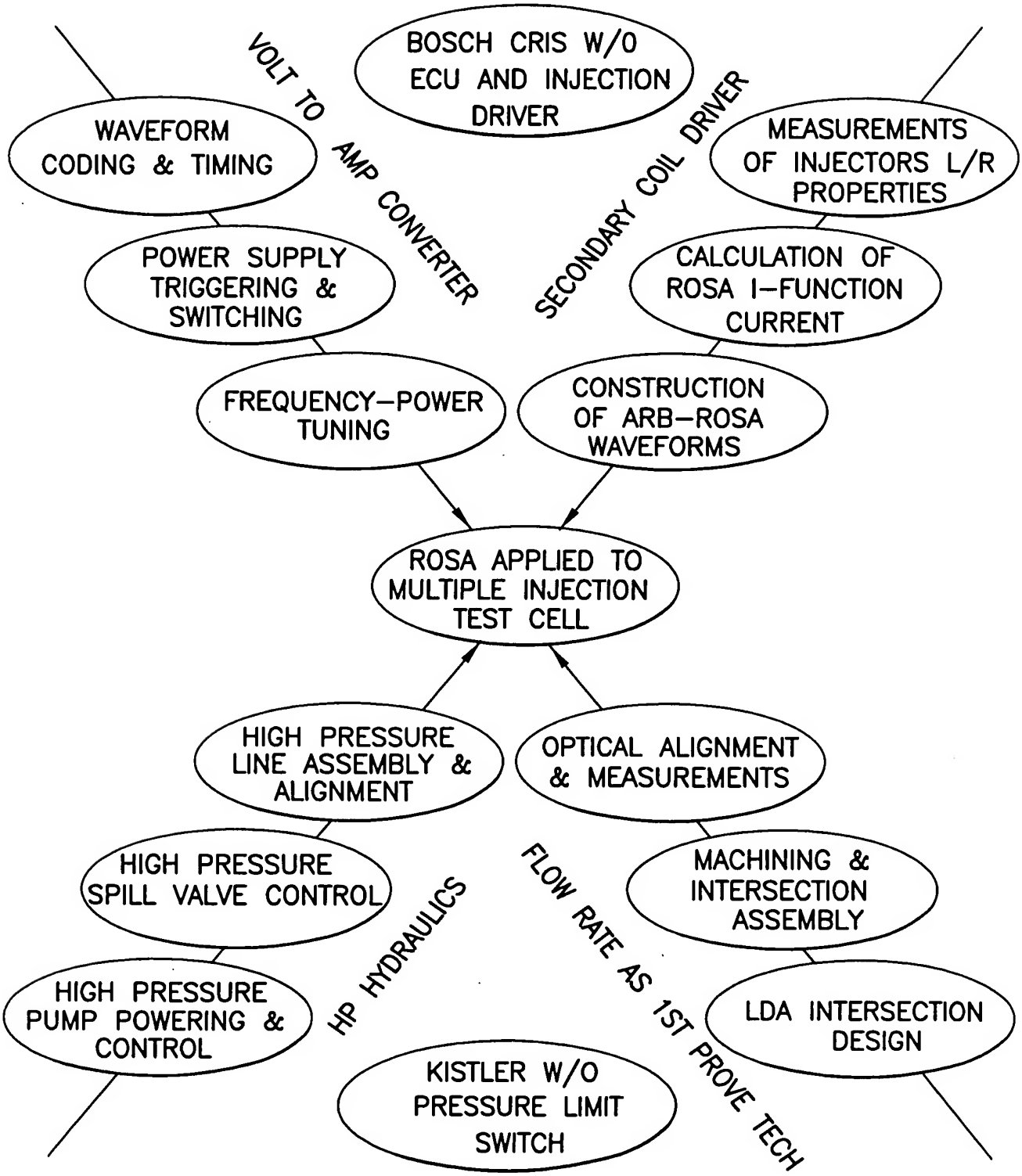

BOSCH CRIS W/O ECU AND INJECTION DRIVER
WAVEFORM CODING & TIMING
VOLT TO AMP CONVERTER
SECONDARY COIL DRIVER
MEASUREMENTS OF INJECTORS L/R PROPERTIES
POWER SUPPLY TRIGGERING & SWITCHING
CALCULATION OF ROSA I-FUNCTION CURRENT
FREQUENCY-POWER TUNING
CONSTRUCTION OF ARB-ROSA WAVEFORMS
ROSA APPLIED TO MULTIPLE INJECTION TEST CELL
HIGH PRESSURE LINE ASSEMBLY & ALIGNMENT
OPTICAL ALIGNMENT & MEASUREMENTS
HIGH PRESSURE SPILL VALVE CONTROL
MACHINING & INTERSECTION ASSEMBLY
HP HYDRAULICS
FLOW RATE AS 1ST PROVE TECH
HIGH PRESSURE PUMP POWERING & CONTROL
LDA INTERSECTION DESIGN
KISTLER W/O PRESSURE LIMIT SWITCH

FIG.26

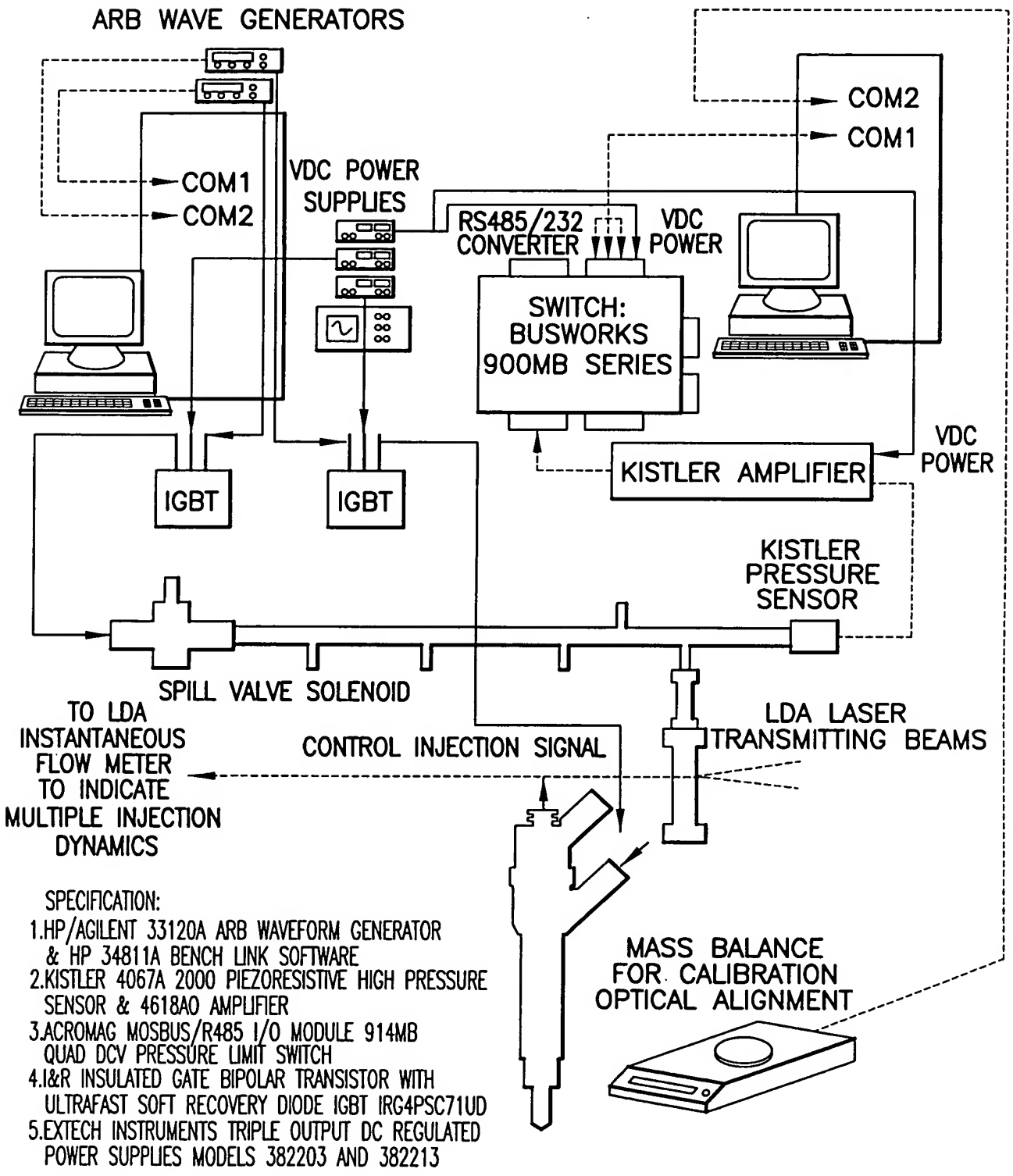

ARB WAVE GENERATORS
COM1
COM2
VDC POWER SUPPLIES
COM2
COM1
RS485/232 CONVERTER
VDC POWER
SWITCH: BUSWORKS 900MB SERIES
KISTLER AMPLIFIER
VDC POWER
IGBT
IGBT
KISTLER PRESSURE SENSOR
SPILL VALVE SOLENOID
TO LDA INSTANTANEOUS FLOW METER TO INDICATE MULTIPLE INJECTION DYNAMICS
CONTROL INJECTION SIGNAL
LDA LASER TRANSMITTING BEAMS
MASS BALANCE FOR CALIBRATION OPTICAL ALIGNMENT
SPECIFICATION:
1.HP/AGILENT 33120A ARB WAVEFORM GENERATOR & HP 34811A BENCH LINK SOFTWARE
2.KISTLER 4067A 2000 PIEZORESISTIVE HIGH PRESSURE SENSOR & 4618A0 AMPLIFIER
3.ACROMAG MOSBUS/R485 I/O MODULE 914MB QUAD DCV PRESSURE LIMIT SWITCH
4.I&R INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE IGBT IRG4PSC71UD
5.EXTECH INSTRUMENTS TRIPLE OUTPUT DC REGULATED POWER SUPPLIES MODELS 382203 AND 382213

FIG.27

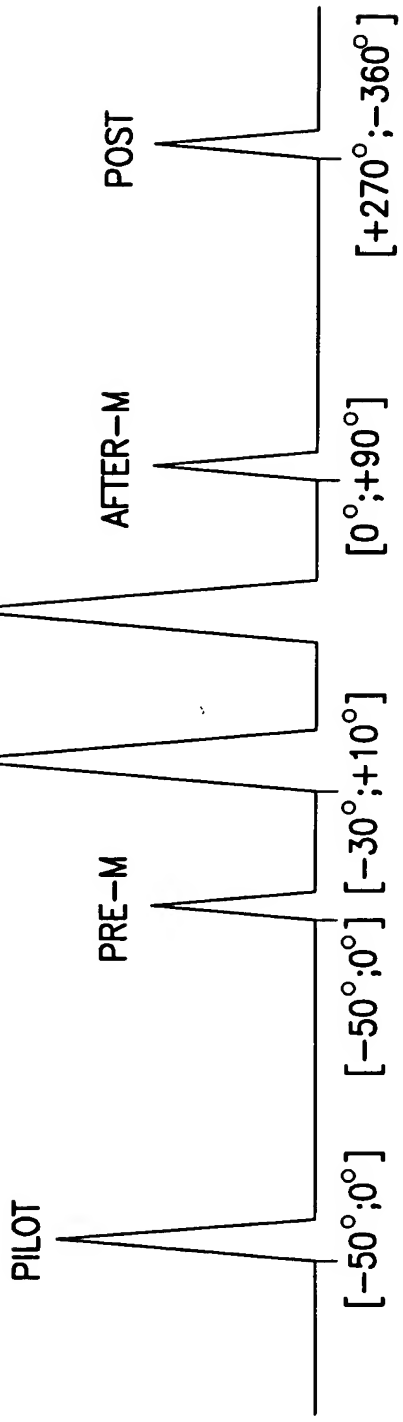


FIG.28

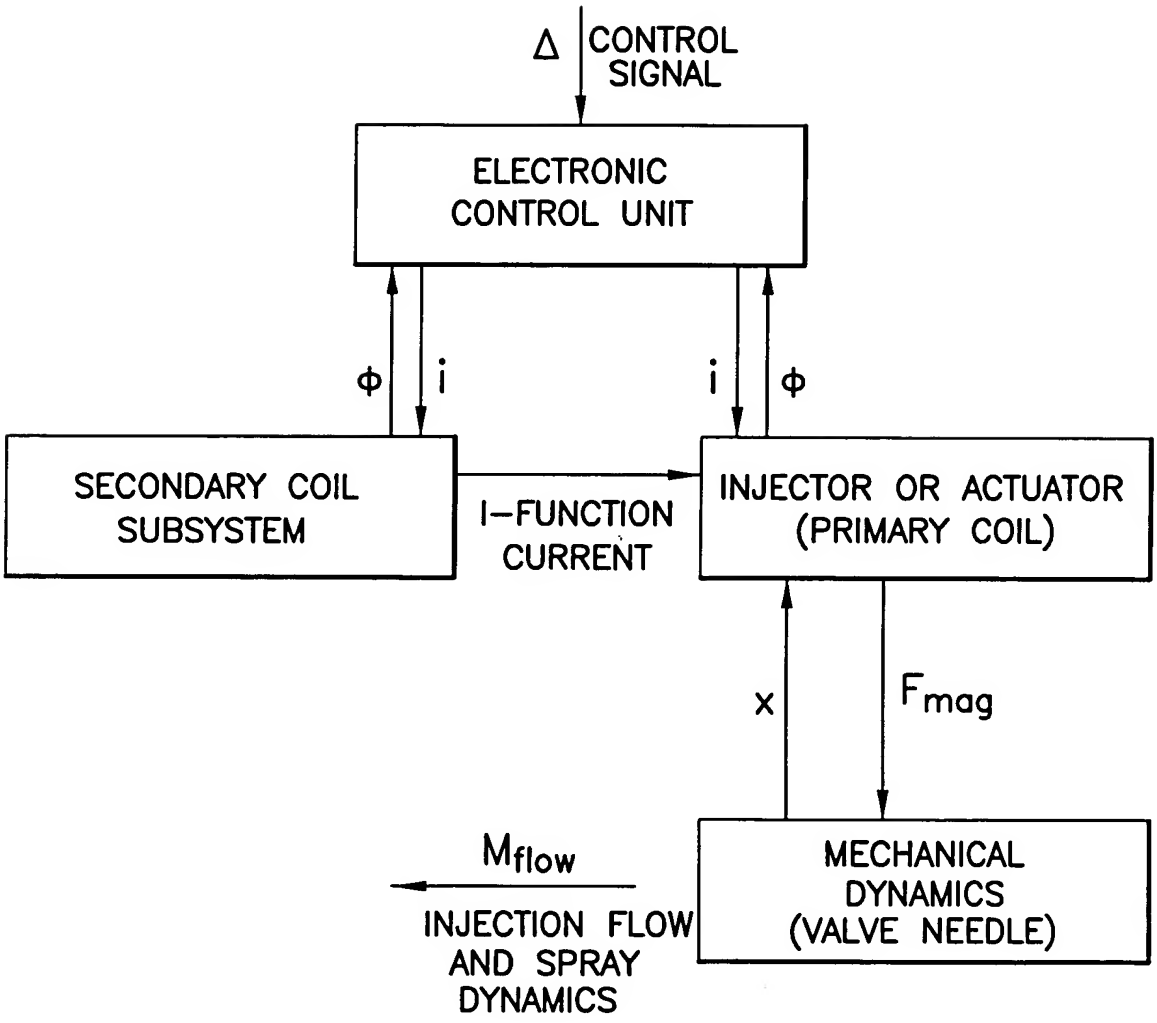

Δ
CONTROL SIGNAL
ELECTRONIC CONTROL UNIT
Φ
i
i
Φ
SECONDARY COIL SUBSYSTEM
I–FUNCTION CURRENT
INJECTOR OR ACTUATOR (PRIMARY COIL)
x
Fmag
Mflow
INJECTION FLOW AND SPRAY DYNAMICS
MECHANICAL DYNAMICS (VALVE NEEDLE)

FIG.29

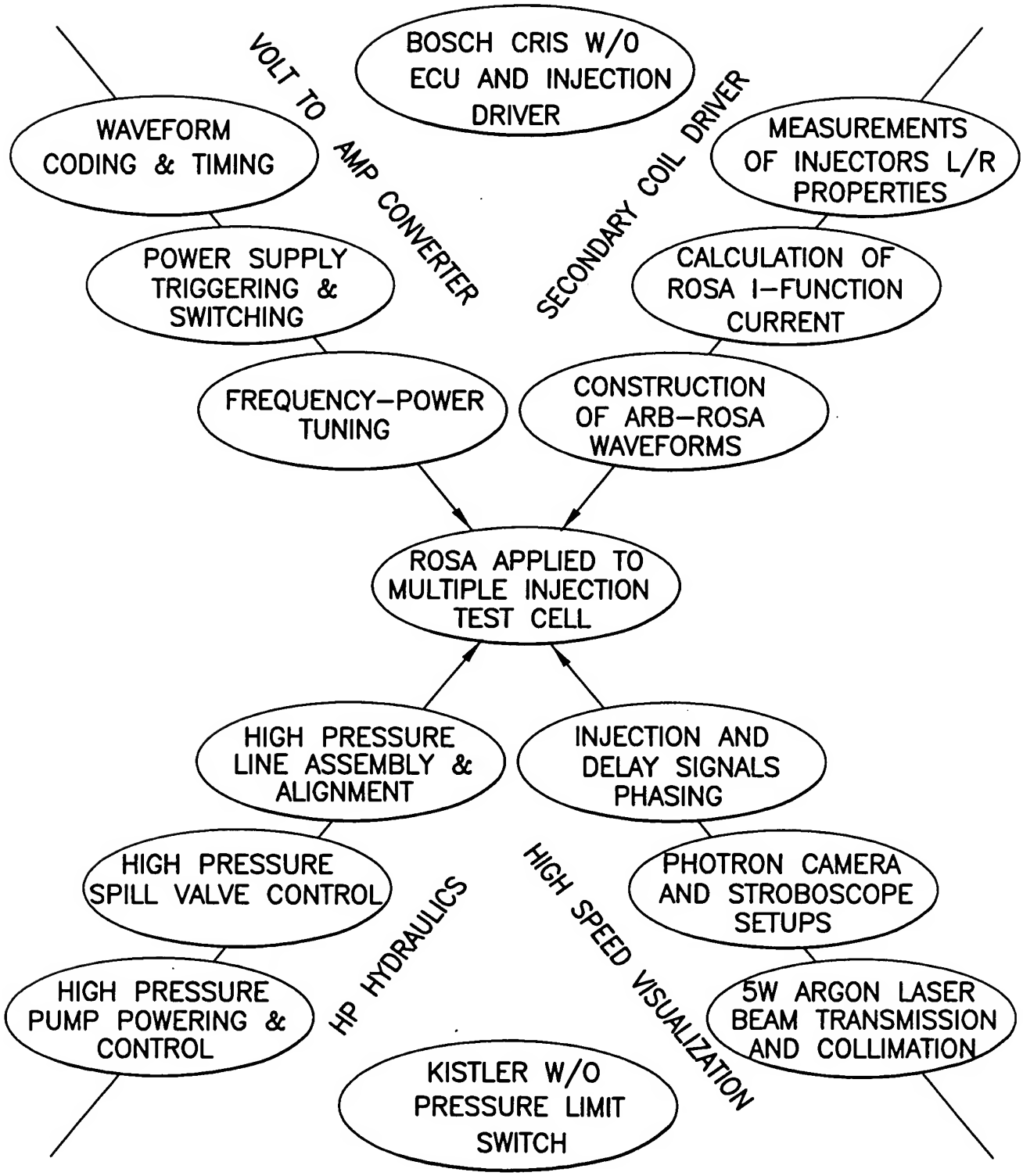
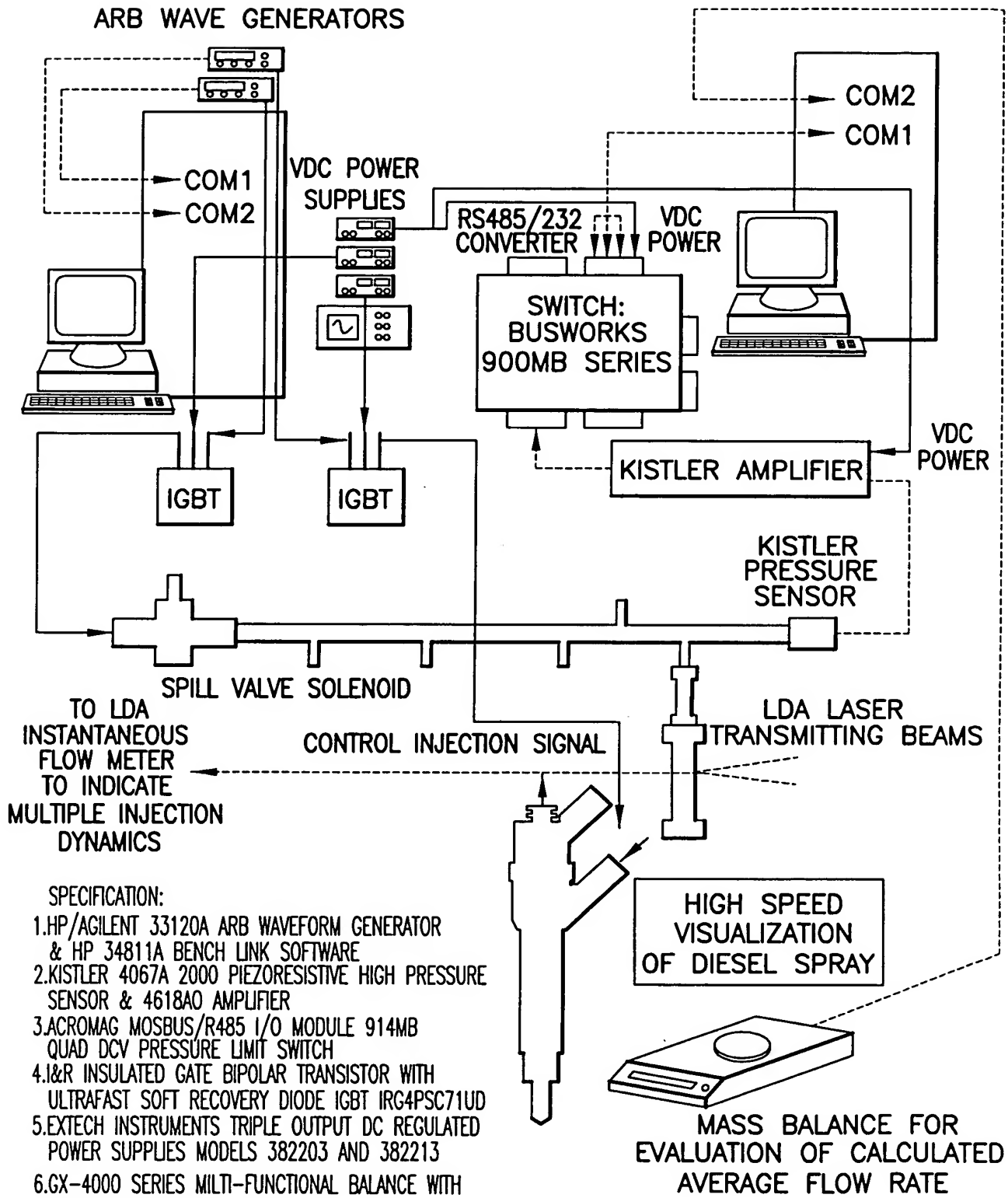

BOSCH CRIS W/O ECU AND INJECTION DRIVER
WAVEFORM CODING & TIMING
VOLT TO AMP CONVERTER
SECONDARY COIL DRIVER
MEASUREMENTS OF INJECTORS L/R PROPERTIES
POWER SUPPLY TRIGGERING & SWITCHING
CALCULATION OF ROSA I-FUNCTION CURRENT
FREQUENCY-POWER TUNING
CONSTRUCTION OF ARB-ROSA WAVEFORMS
ROSA APPLIED TO MULTIPLE INJECTION TEST CELL
HIGH PRESSURE LINE ASSEMBLY & ALIGNMENT
INJECTION AND DELAY SIGNALS PHASING
HIGH PRESSURE SPILL VALVE CONTROL
HP HYDRAULICS
HIGH SPEED VISUALIZATION
PHOTRON CAMERA AND STROBOSCOPE SETUPS
HIGH PRESSURE PUMP POWERING & CONTROL
5W ARGON LASER BEAM TRANSMISSION AND COLLIMATION
KISTLER W/O PRESSURE LIMIT SWITCH

FIG.30



SPECIFICATION:

1. HP/AGILENT 33120A ARB WAVEFORM GENERATOR & HP 34811A BENCH LINK SOFTWARE
2. KISTLER 4067A 2000 PIEZORESISTIVE HIGH PRESSURE SENSOR & 4618A0 AMPLIFIER
3. ACROMAG MOSBUS/R485 I/O MODULE 914MB QUAD DCV PRESSURE LIMIT SWITCH
4. I&R INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE IGBT IRG4PSC71UD
5. EXTECH INSTRUMENTS TRIPLE OUTPUT DC REGULATED POWER SUPPLIES MODELS 382203 AND 382213
6. GX-4000 SERIES MILTI-FUNCTIONAL BALANCE WITH A&D WinCT 2.00 SOFTWARE
7. DAN TEC/INVENT MEASUREMENT TECHNOLOGY G mb H PDA/LDA ENTIRE SYSTEM
8. PHOTRON ULTIMA SE CCD HIGH SPEED CAMERA

FIG.31

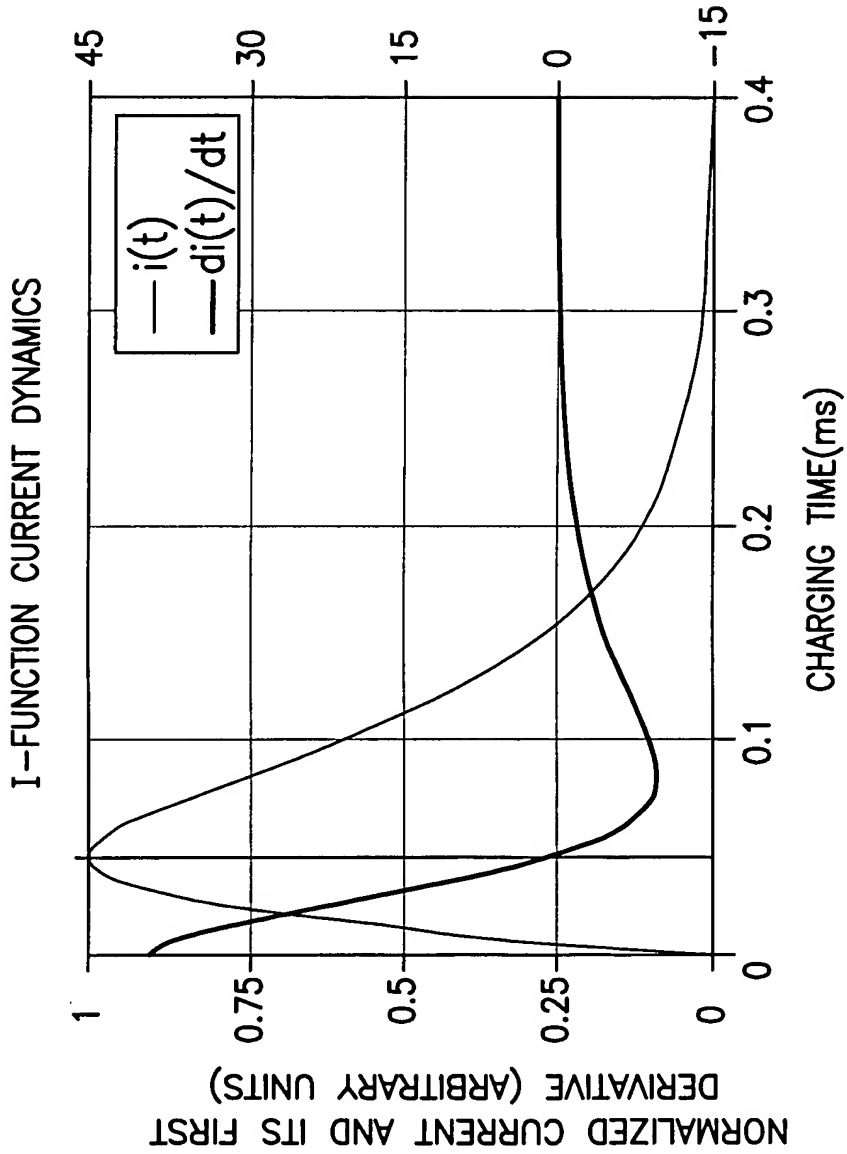

I-FUNCTION CURRENT DYNAMICS
i(t)
di(t)/dt
NORMALIZED CURRENT AND ITS FIRST DERIVATIVE (ARBITRARY UNITS)
CHARGING TIME(ms)
1
0.75
0.5
0.25
0
45
30
15
0
-15
0
0.1
0.2
0.3
0.4

FIG.32

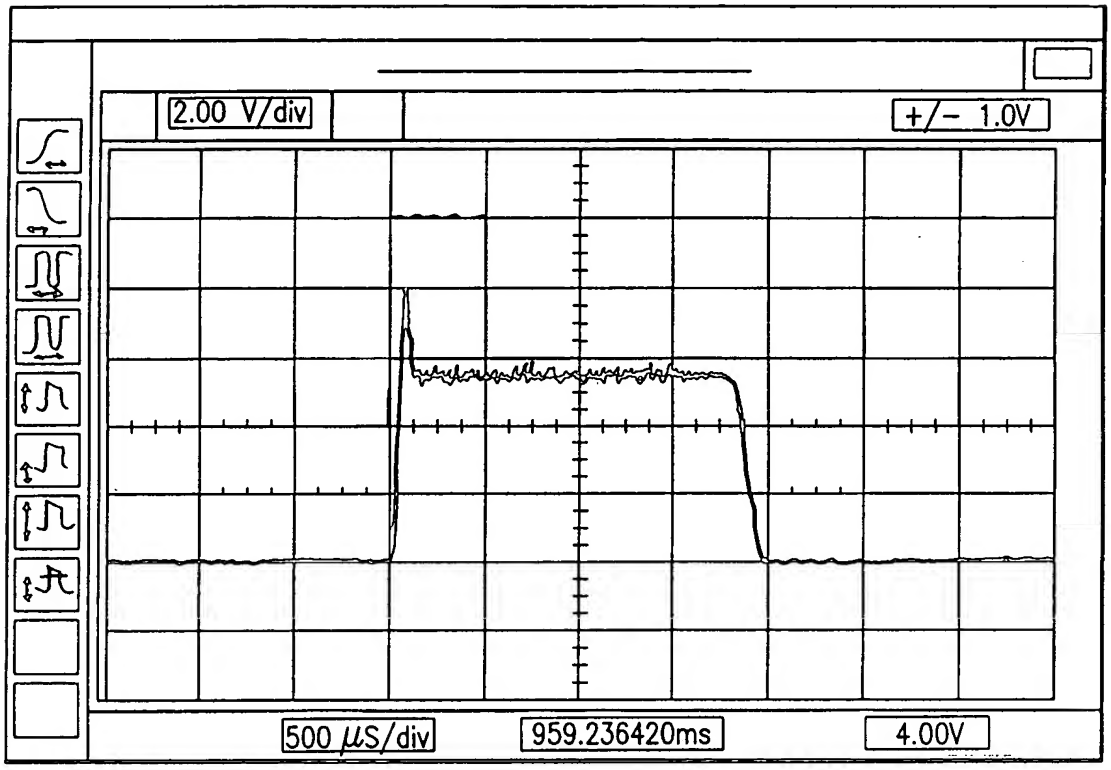

2.00 V/div
+/- 1.0V
500 µS/div
959.236420ms
4.00V

FIG.33

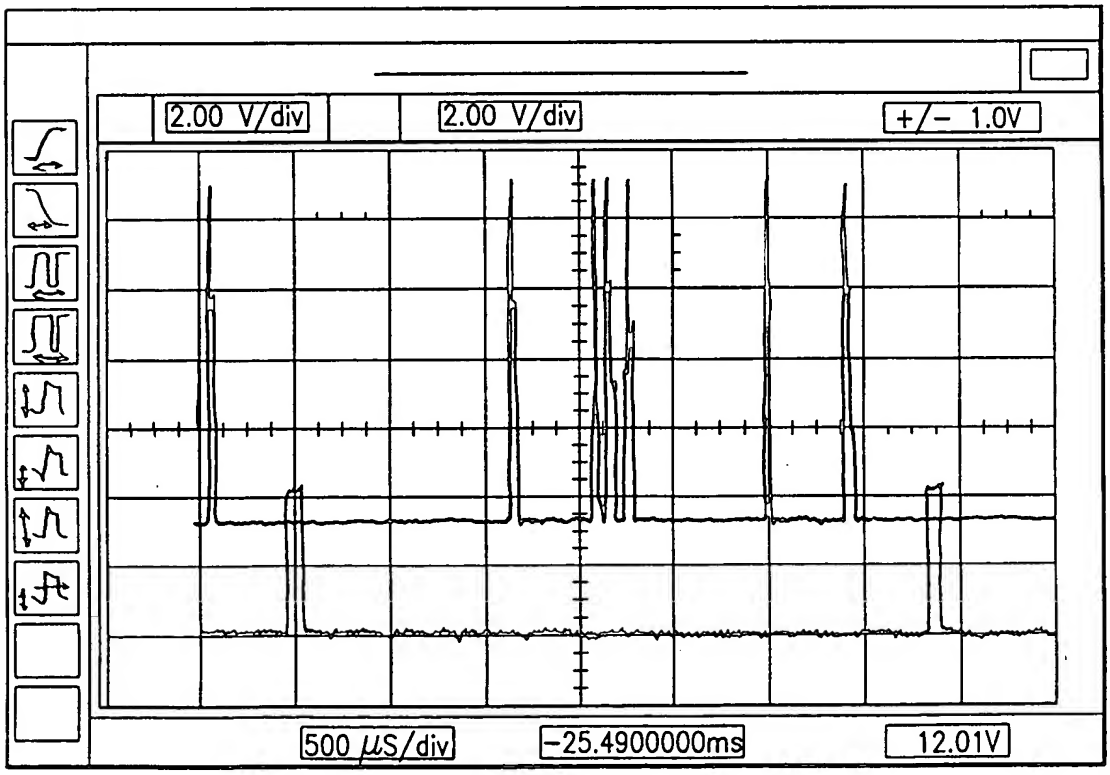

2.00 V/div
2.00 V/div
+/- 1.0V
500 µS/div
-25.4900000ms
12.01V

FIG.34

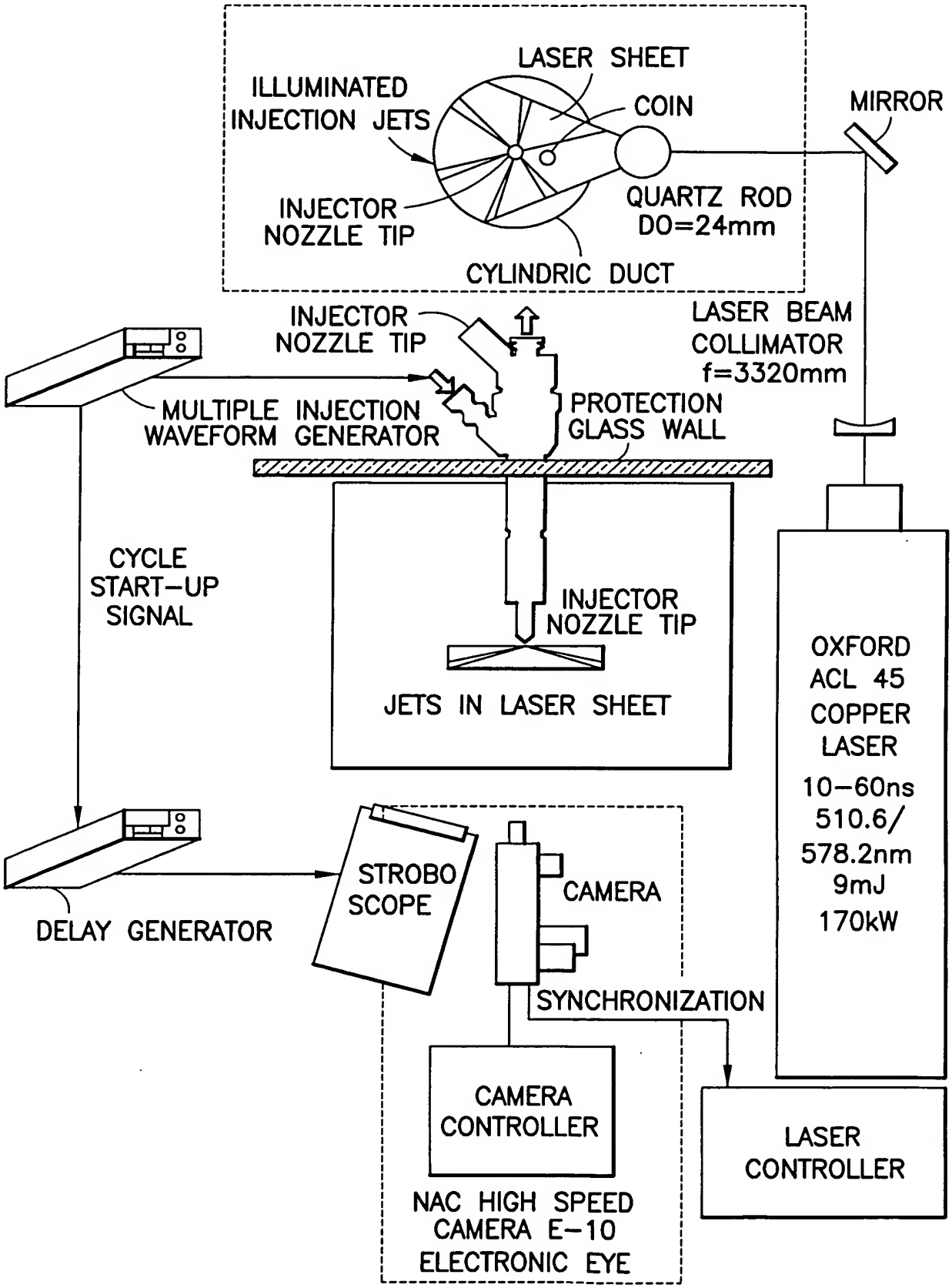
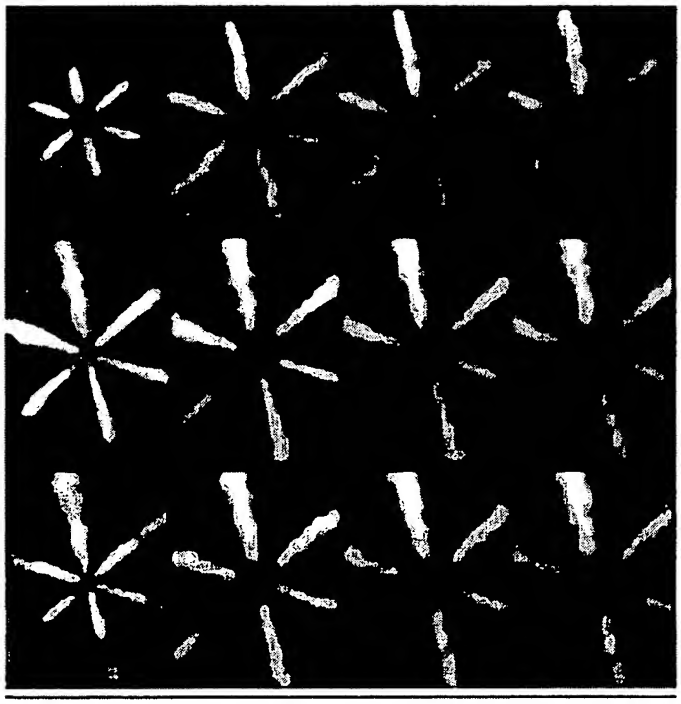

LASER SHEET
ILLUMINATED INJECTION JETS
COIN
MIRROR
INJECTOR NOZZLE TIP
QUARTZ ROD DO=24mm
CYLINDRIC DUCT
INJECTOR NOZZLE TIP
LASER BEAM COLLIMATOR f=3320mm
MULTIPLE INJECTION WAVEFORM GENERATOR
PROTECTION GLASS WALL
CYCLE START-UP SIGNAL
INJECTOR NOZZLE TIP
JETS IN LASER SHEET
OXFORD ACL 45 COPPER LASER
10-60ns
510.6/ 578.2nm
9mJ
170kW
STROBO SCOPE
CAMERA
DELAY GENERATOR
SYNCHRONIZATION
CAMERA CONTROLLER
LASER CONTROLLER
NAC HIGH SPEED CAMERA E-10 ELECTRONIC EYE

FIG.35



EXAMPLE OF SPRAY
AT LOW CAMERA SPEED

FIG.36

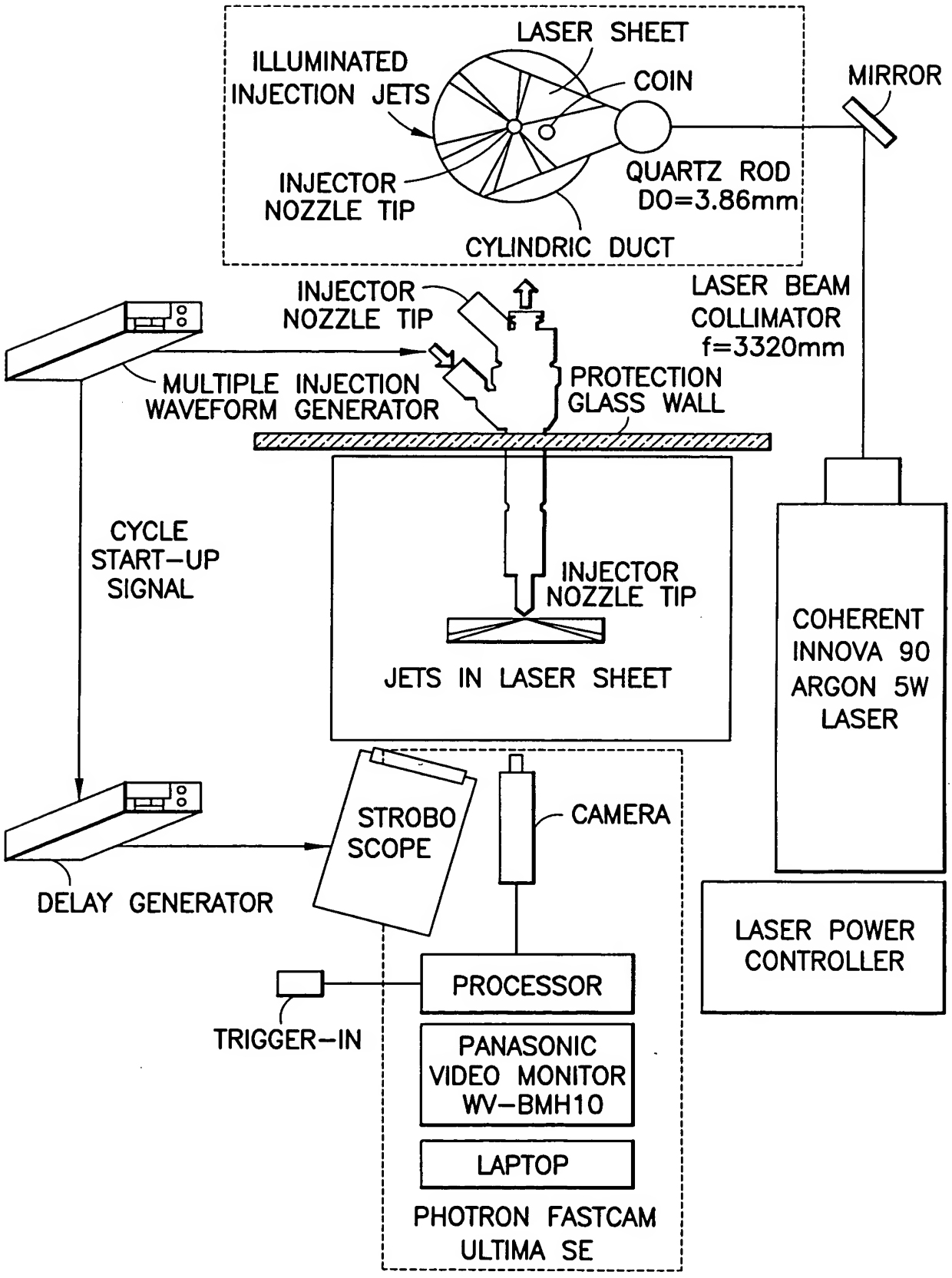
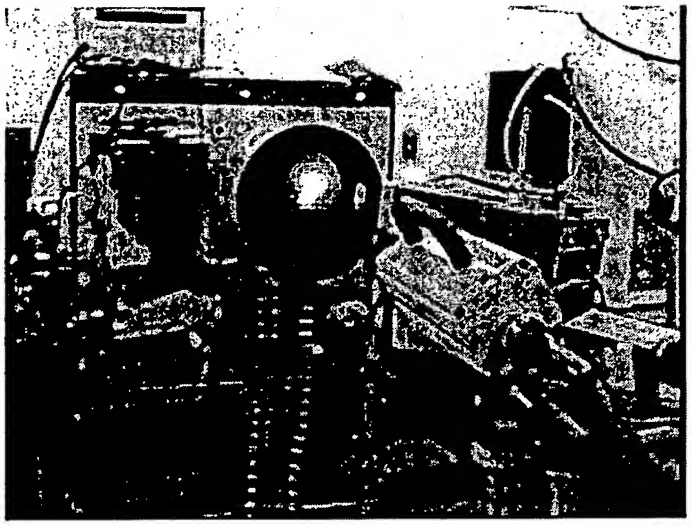
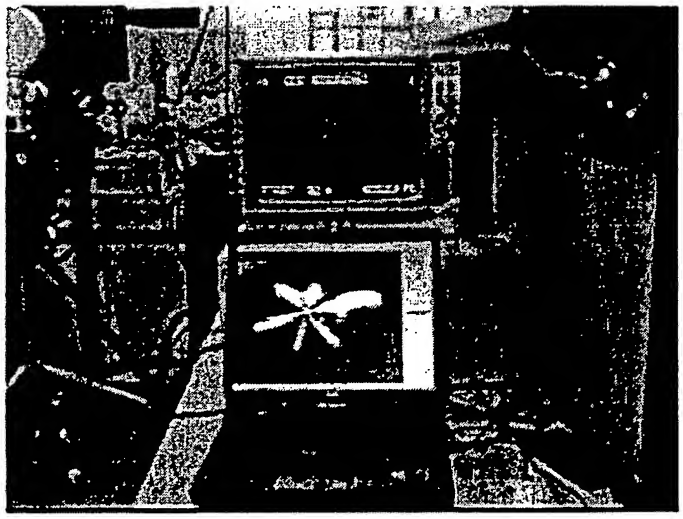

LASER SHEET
ILLUMINATED INJECTION JETS
COIN
MIRROR
INJECTOR NOZZLE TIP
QUARTZ ROD DO=3.86mm
CYLINDRIC DUCT
INJECTOR NOZZLE TIP
LASER BEAM COLLIMATOR f=3320mm
MULTIPLE INJECTION WAVEFORM GENERATOR
PROTECTION GLASS WALL
CYCLE START-UP SIGNAL
INJECTOR NOZZLE TIP
JETS IN LASER SHEET
COHERENT INNOVA 90 ARGON 5W LASER
STROBO SCOPE
CAMERA
DELAY GENERATOR
LASER POWER CONTROLLER
PROCESSOR
TRIGGER-IN
PANASONIC VIDEO MONITOR WV-BMH10
LAPTOP
PHOTRON FASTCAM ULTIMA SE

FIG.37



A. INJECTOR SETUP WITH STROBOSCOPE

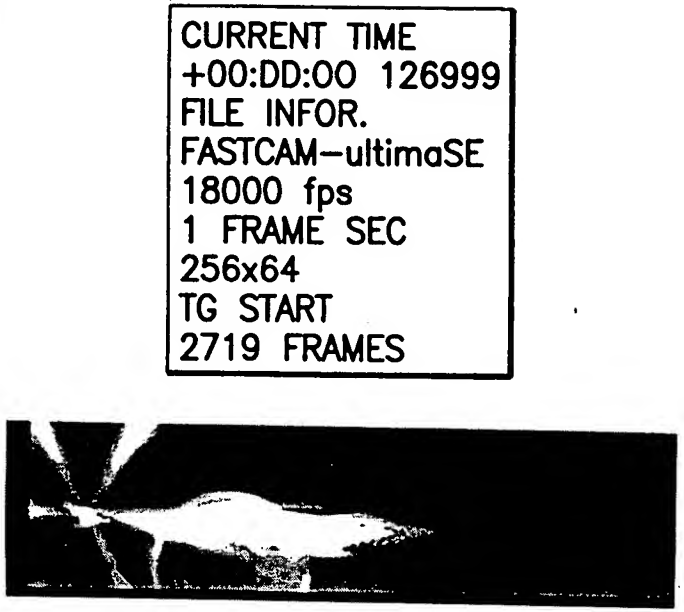


B. SIGNAL PROCESSOR WITH MONITOR

FIG.38

VISUALIZATION SPEEDS OF 9,000; 18,000; 27,000 AND 40,500 fps

VISUALIZATION OPTICS SETUP
WHITE DISC IS US QUARTER



t=0126333 s

PILOT SHOT IN SIX-SHOT INJECTION: ENGINE SPEED 2,400 RPM, FRAME DURATION 55.56 μs, COIN SIZE 24.76 mm.

FIG.39

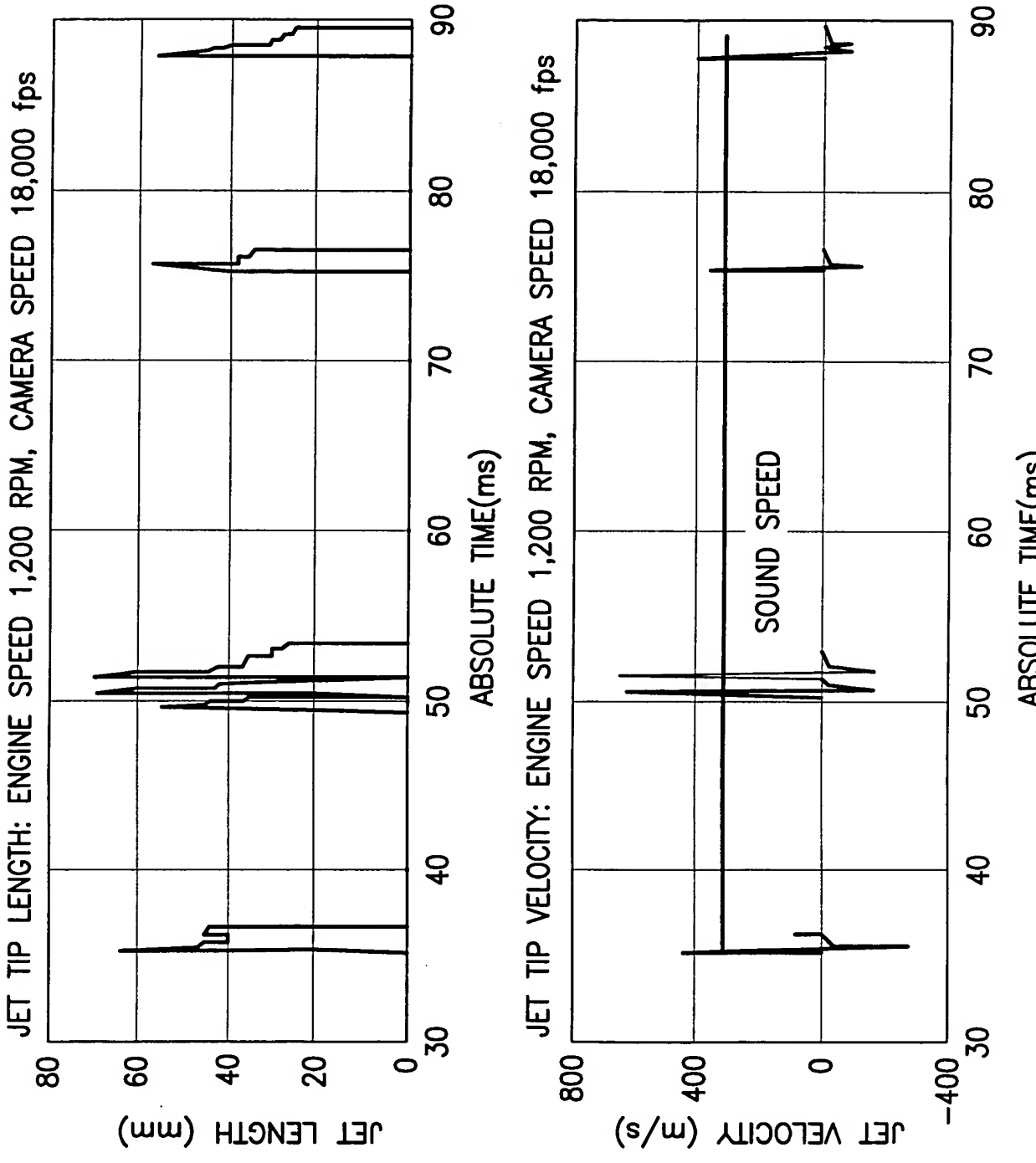

JET TIP LENGTH: ENGINE SPEED 1,200 RPM, CAMERA SPEED 18,000 fps
JET LENGTH (mm)
0
20
40
60
80
30
40
50
60
70
80
90
ABSOLUTE TIME(ms)
JET TIP VELOCITY: ENGINE SPEED 1,200 RPM, CAMERA SPEED 18,000 fps
JET VELOCITY (m/s)
800
400
0
−400
SOUND SPEED
30
40
50
60
70
80
90
ABSOLUTE TIME(ms)

FIG.40

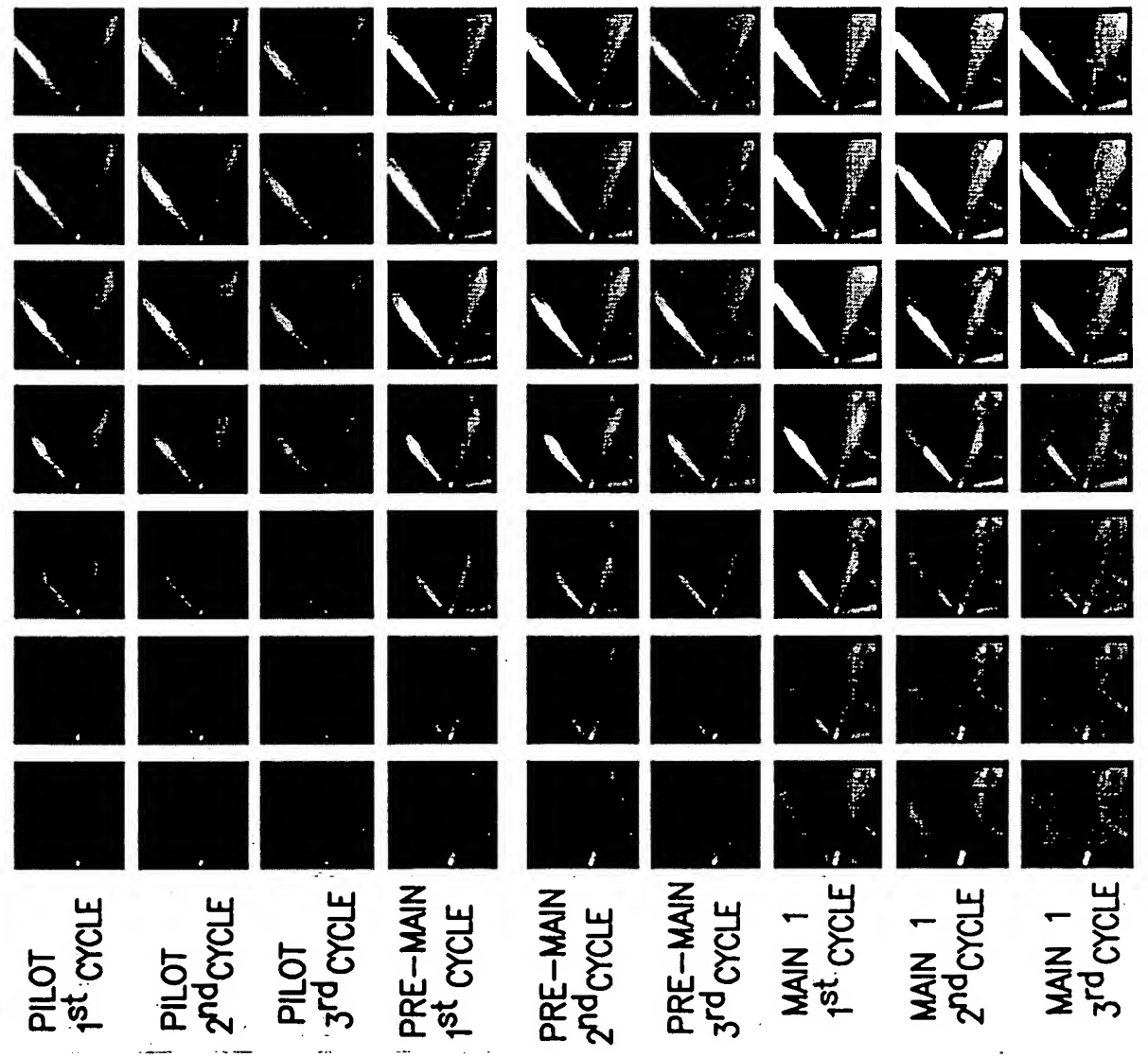

PILOT 1st CYCLE
PILOT 2nd CYCLE
PILOT 3rd CYCLE
PRE-MAIN 1st CYCLE
PRE-MAIN 2nd CYCLE
PRE-MAIN 3rd CYCLE
MAIN 1 1st CYCLE
MAIN 1 2nd CYCLE
MAIN 1 3rd CYCLE

FIG. 41

WAVEFORM ELECTRONIC SETUP, ENGINE SPEED 3,600 RPM									HIGH SPEED CAMERA RECORD AT SPEED OF 40,500 FPS							
		DURATION				PHASES				DURATION				PHASES		
		PTS	MS	DEG		PTS	MS	DEG		FRAMES	MS	DEG		FRAME	MS	DEG
	PERIOD	16000	33.3	360	PERIOD	16000	33.3	360		1350	33.333	360	PERIOD	1350	33.333	360
3	Main	288	0.6	6.5		8000	16.667	180		11	0.272	2.9		1969	17.210	185.9
	dwell_1	96	0.2	2.2						21	0.518	5.6				
2	Pre_M	192	0.4	4.3		7712	16.067	173.5		8	0.198	2.1		1940	16.494	178.1
1	Pilot	192	0.4	4.3		5600	11.667	126.0		8	0.198	2.1		1762	12.099	130.7
	dwell_2	240	0.5	5.4						28	0.691	7.5				
4	Main_2	240	0.5	5.4		8528	17.767	191.9		14	0.346	3.7		2008	18.173	196.3
5	After_M	192	0.4	4.3		12000	25.000	270.0		9	0.222	2.4		2302	25.432	274.7
6	Post	192	0.4	4.3		14000	29.167	315.0		7	0.173	1.9		2472	29.630	320.0
	Pilot–to–Pre_M					1920	4.000	43.2		Pilot–to–Pre_M				170	4.198	45
	Pre_M–to–Main1					96	0.200	2.16		Pre_M–to–Main1				21	0.519	6
	Main1–to–Main2					240	0.500	5		Main1–to–Main2				28	0.691	7
	Main2–to–AfterM					3232	6.733	73		Main2–to–AfterM				280	6.914	75
	AfterM–to–Post					1808	3.767	41		AfterM–to–Post				161	3.975	43

FIG.42

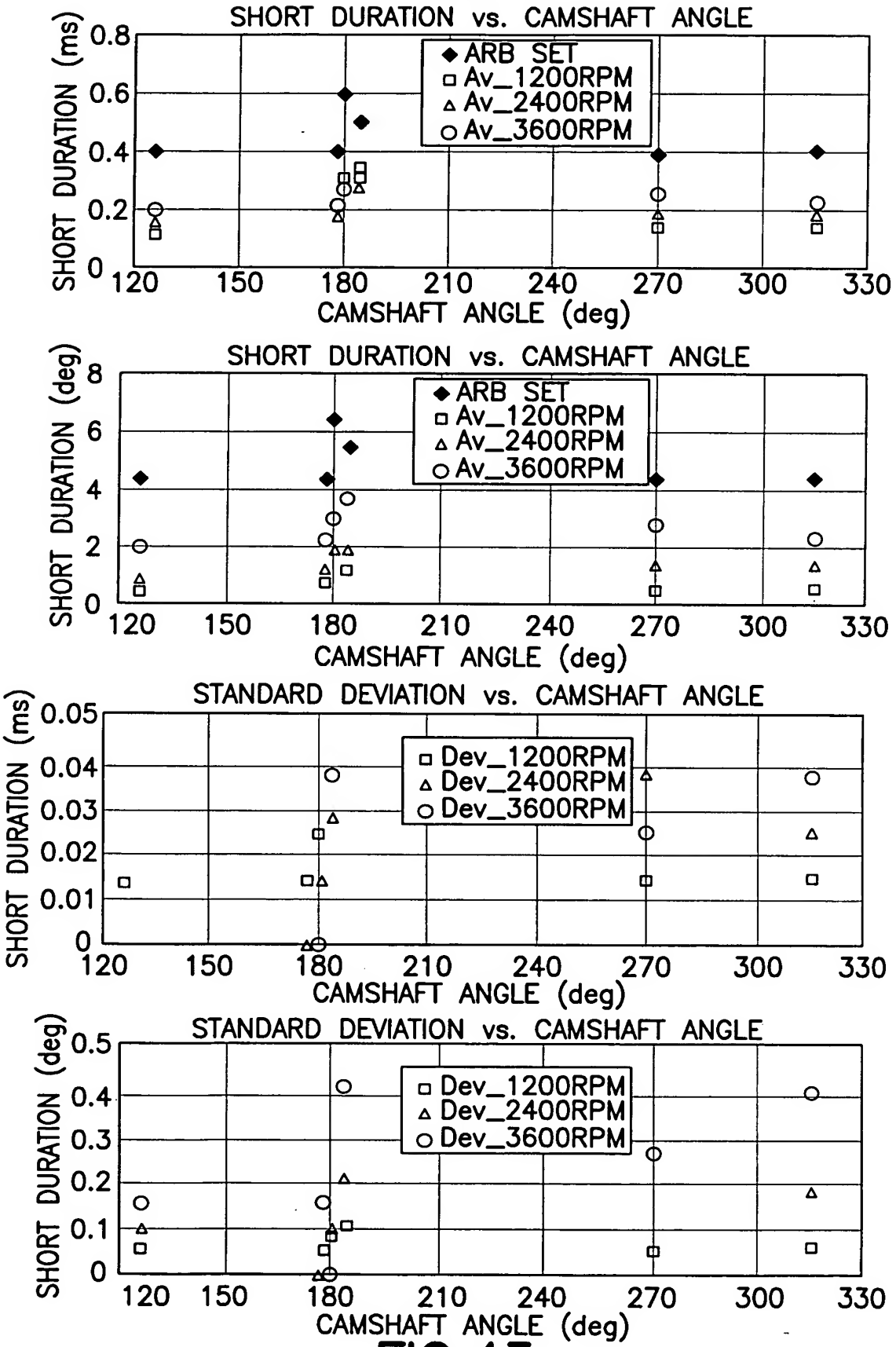

SHORT DURATION vs. CAMSHAFT ANGLE
SHORT DURATION (ms)
0.8
0.6
0.4
0.2
0
ARB SET
Av_1200RPM
Av_2400RPM
Av_3600RPM
120 150 180 210 240 270 300 330
CAMSHAFT ANGLE (deg)
SHORT DURATION vs. CAMSHAFT ANGLE
SHORT DURATION (deg)
8
6
4
2
0
ARB SET
Av_1200RPM
Av_2400RPM
Av_3600RPM
120 150 180 210 240 270 300 330
CAMSHAFT ANGLE (deg)
STANDARD DEVIATION vs. CAMSHAFT ANGLE
SHORT DURATION (ms)
0.05
0.04
0.03
0.02
0.01
0
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
120 150 180 210 240 270 300 330
CAMSHAFT ANGLE (deg)
STANDARD DEVIATION vs. CAMSHAFT ANGLE
SHORT DURATION (deg)
0.5
0.4
0.3
0.2
0.1
0
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
120 150 180 210 240 270 300 330
CAMSHAFT ANGLE (deg)

FIG.43

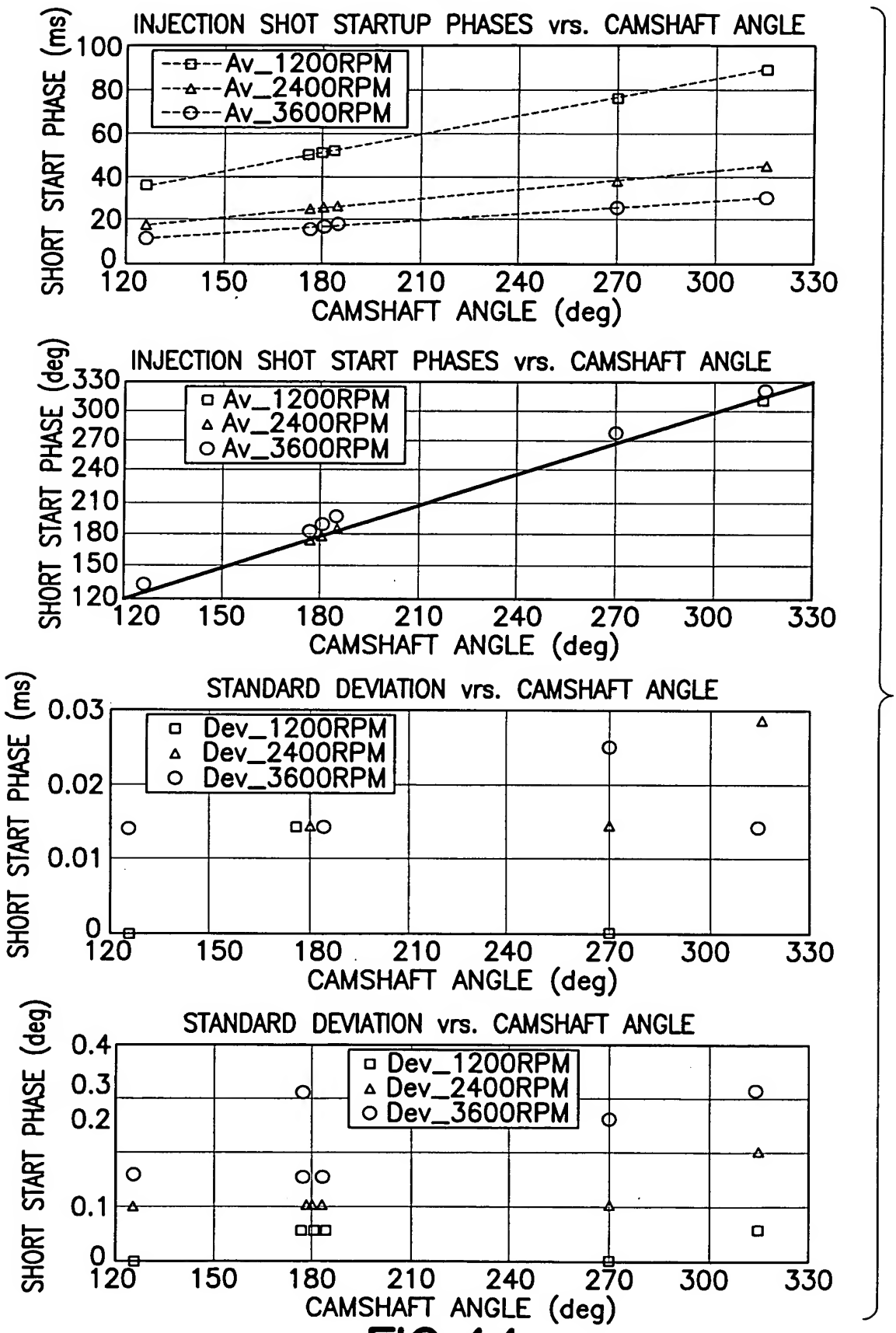

INJECTION SHOT STARTUP PHASES vrs. CAMSHAFT ANGLE
SHORT START PHASE (ms)
100
80
60
40
20
0
Av_1200RPM
Av_2400RPM
Av_3600RPM
120
150
180
210
240
270
300
330
CAMSHAFT ANGLE (deg)
INJECTION SHOT START PHASES vrs. CAMSHAFT ANGLE
SHORT START PHASE (deg)
330
300
270
240
210
180
150
120
Av_1200RPM
Av_2400RPM
Av_3600RPM
CAMSHAFT ANGLE (deg)
STANDARD DEVIATION vrs. CAMSHAFT ANGLE
SHORT START PHASE (ms)
0.03
0.02
0.01
0
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
CAMSHAFT ANGLE (deg)
STANDARD DEVIATION vrs. CAMSHAFT ANGLE
SHORT START PHASE (deg)
0.4
0.3
0.2
0.1
0
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
CAMSHAFT ANGLE (deg)

FIG.44

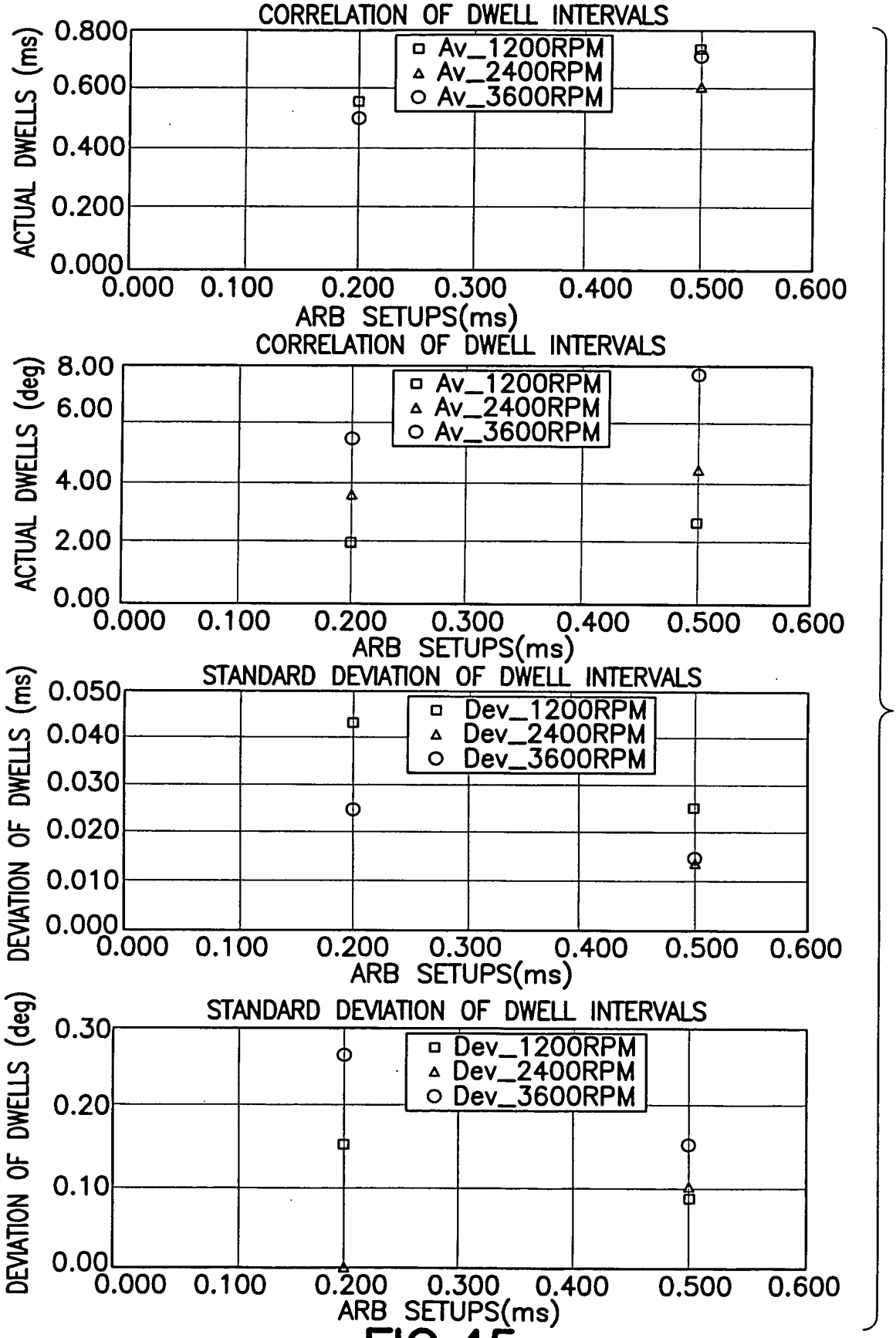

CORRELATION OF DWELL INTERVALS
ACTUAL DWELLS (ms)
0.800
0.600
0.400
0.200
0.000
Av_1200RPM
Av_2400RPM
Av_3600RPM
0.000 0.100 0.200 0.300 0.400 0.500 0.600
ARB SETUPS(ms)
CORRELATION OF DWELL INTERVALS
ACTUAL DWELLS (deg)
8.00
6.00
4.00
2.00
0.00
Av_1200RPM
Av_2400RPM
Av_3600RPM
0.000 0.100 0.200 0.300 0.400 0.500 0.600
ARB SETUPS(ms)
STANDARD DEVIATION OF DWELL INTERVALS
DEVIATION OF DWELLS (ms)
0.050
0.040
0.030
0.020
0.010
0.000
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
0.000 0.100 0.200 0.300 0.400 0.500 0.600
ARB SETUPS(ms)
STANDARD DEVIATION OF DWELL INTERVALS
DEVIATION OF DWELLS (deg)
0.30
0.20
0.10
0.00
Dev_1200RPM
Dev_2400RPM
Dev_3600RPM
0.000 0.100 0.200 0.300 0.400 0.500 0.600
ARB SETUPS(ms)

FIG.45

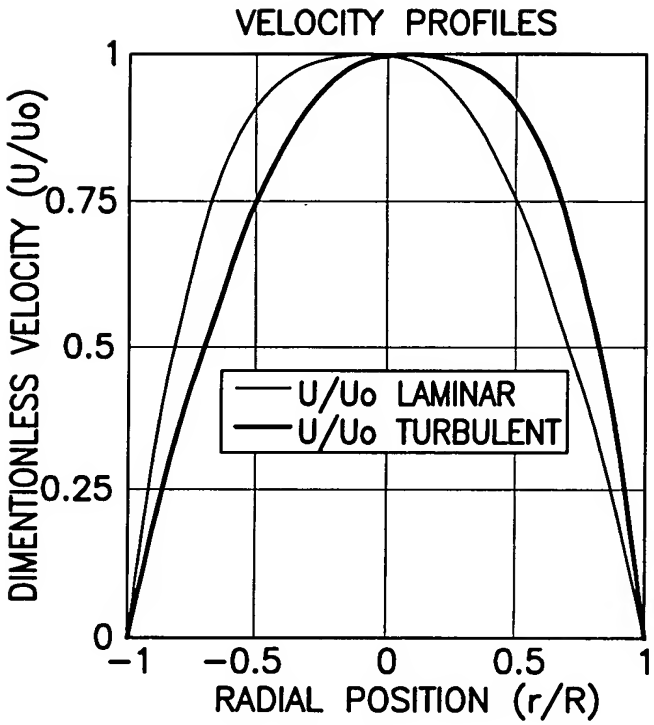

VELOCITY PROFILES
DIMENTIONLESS VELOCITY (U/Uo)
1
0.75
0.5
0.25
0
−1
−0.5
0
0.5
1
RADIAL POSITION (r/R)
U/Uo LAMINAR
U/Uo TURBULENT

FIG.46

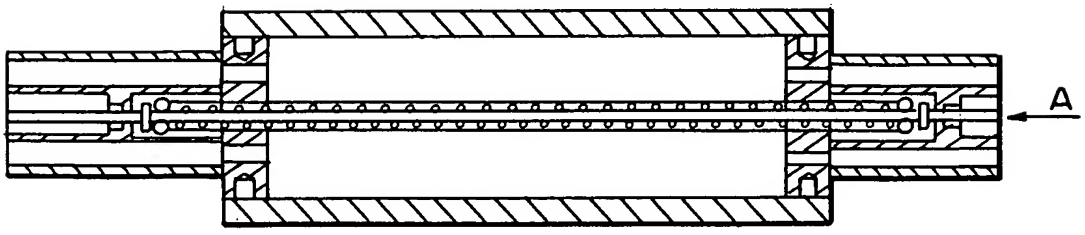

A

FIG.48

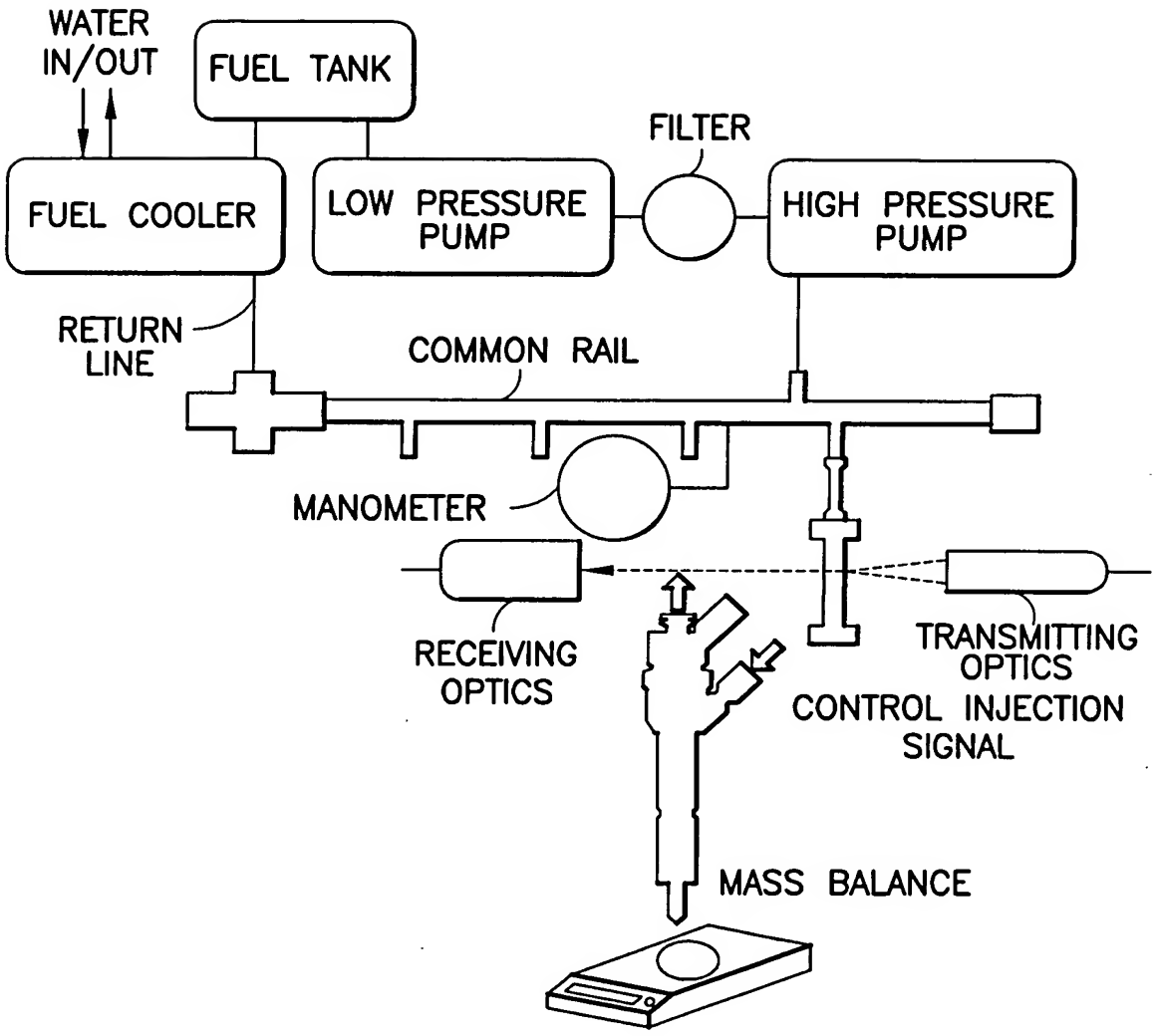

WATER
IN/OUT
FUEL TANK
FILTER
FUEL COOLER
LOW PRESSURE
PUMP
HIGH PRESSURE
PUMP
RETURN
LINE
COMMON RAIL
MANOMETER
RECEIVING
OPTICS
TRANSMITTING
OPTICS
CONTROL INJECTION
SIGNAL
MASS BALANCE

FIG.47

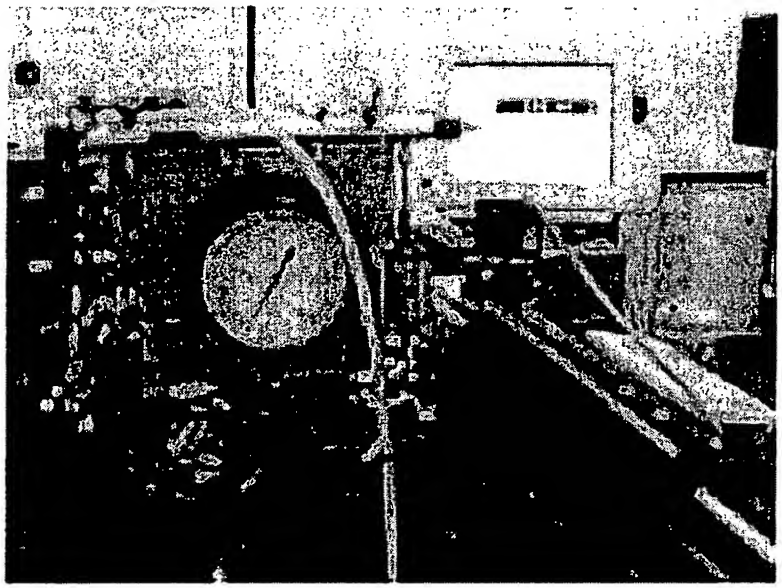


FIG.49

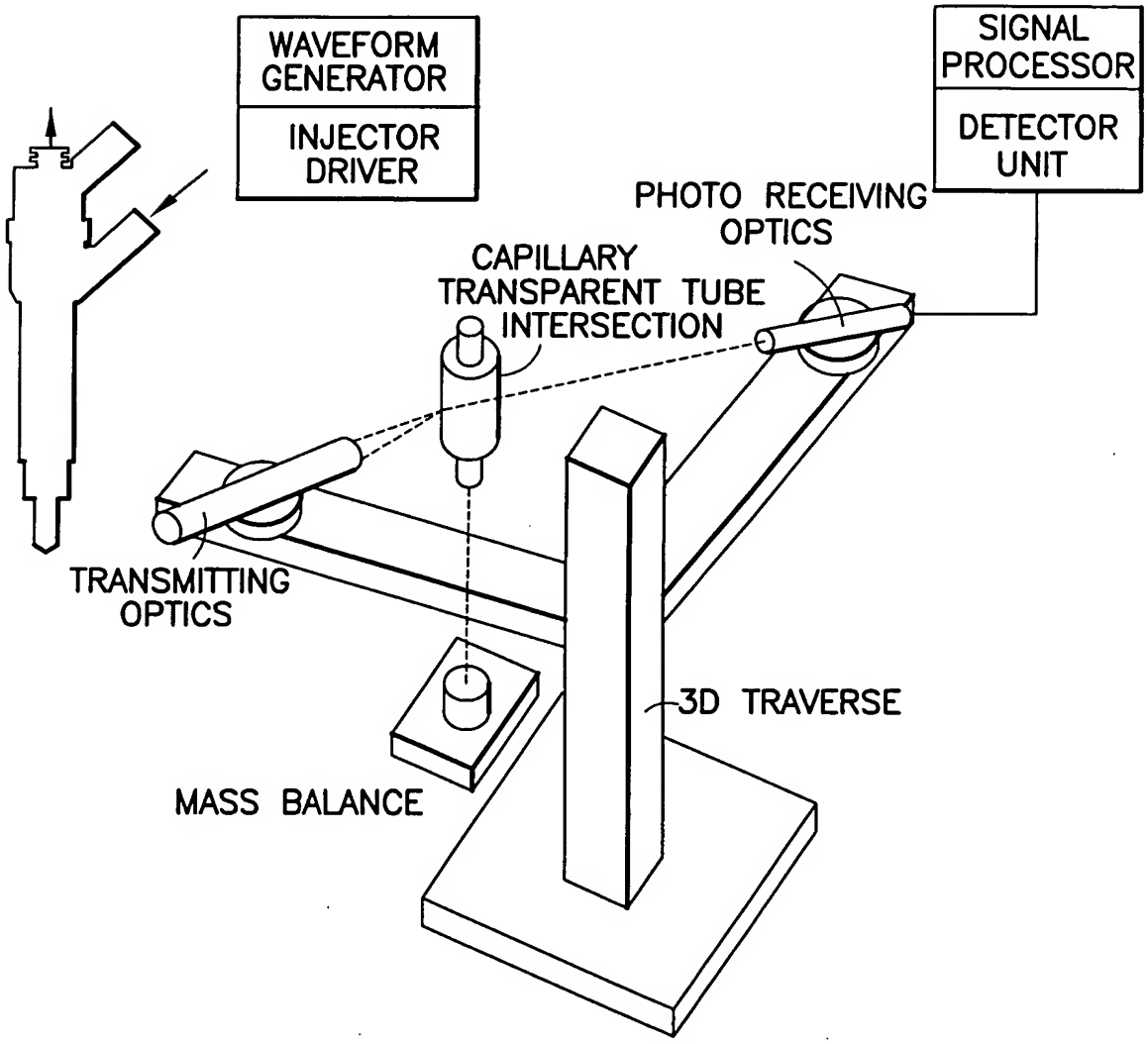

WAVEFORM GENERATOR
INJECTOR DRIVER
SIGNAL PROCESSOR
DETECTOR UNIT
PHOTO RECEIVING OPTICS
CAPILLARY TRANSPARENT TUBE INTERSECTION
TRANSMITTING OPTICS
3D TRAVERSE
MASS BALANCE

FIG.50

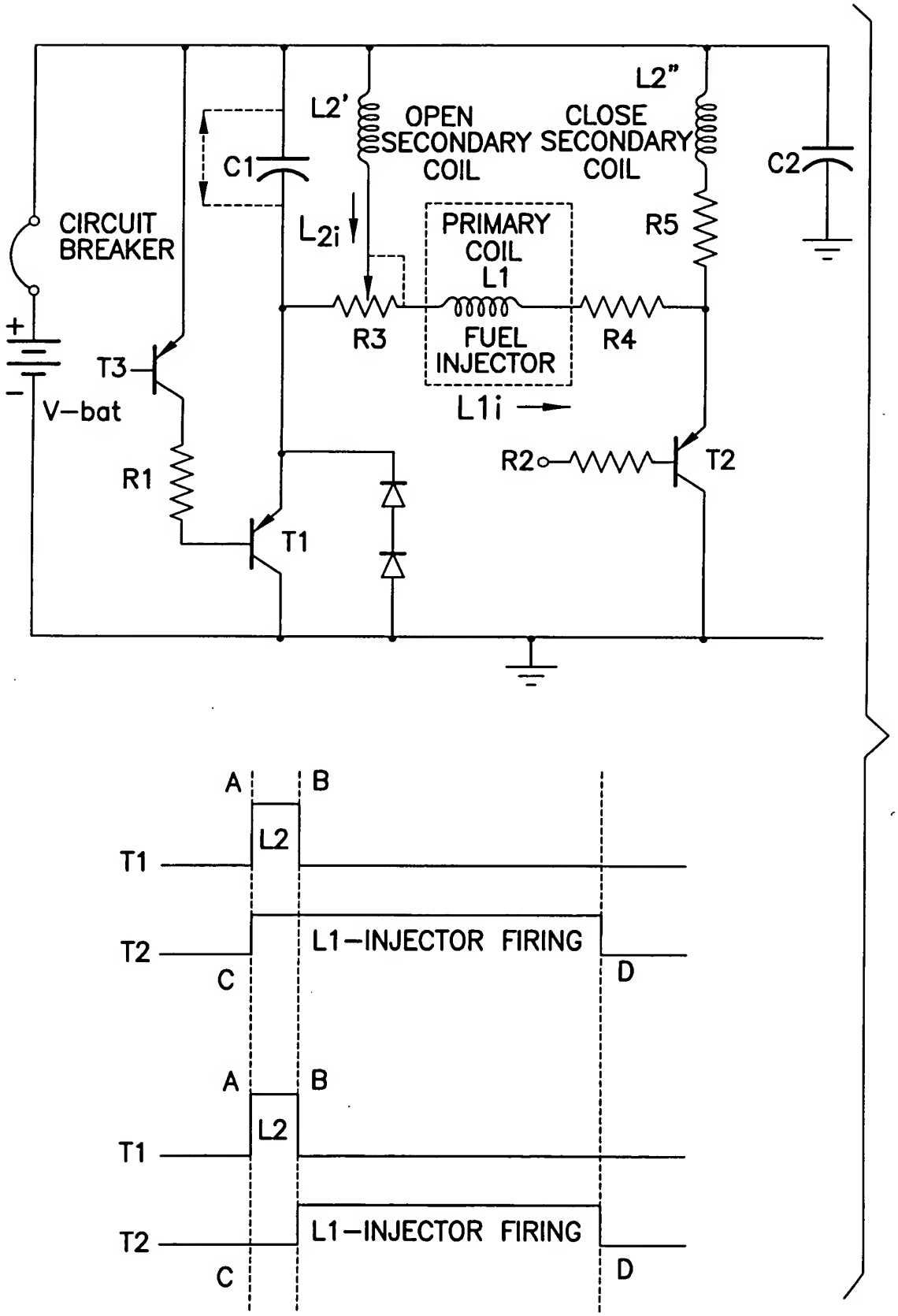
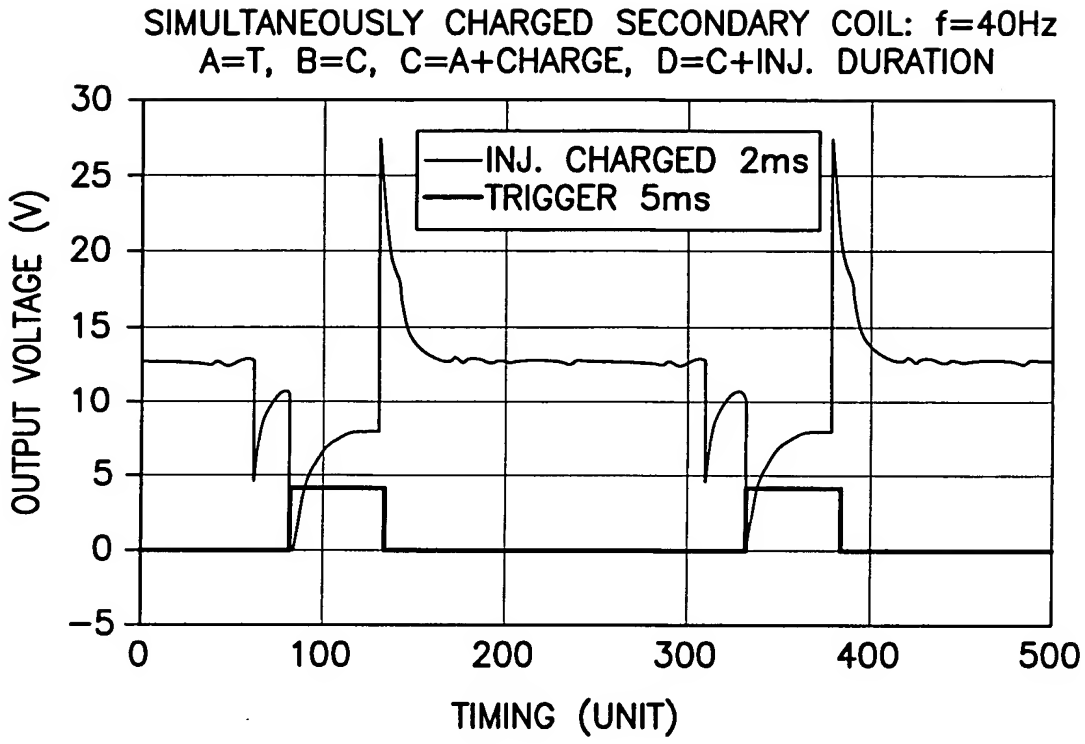

L2"
L2'
OPEN SECONDARY COIL
CLOSE SECONDARY COIL
C1
C2
CIRCUIT BREAKER
L2i
PRIMARY COIL L1
R5
R3
FUEL INJECTOR
R4
T3
V-bat
L1i
R2
T2
R1
T1
A
B
L2
T1
T2
L1-INJECTOR FIRING
C
D
A
B
L2
T1
T2
L1-INJECTOR FIRING
C
D

FIG.51


SIMULTANEOUSLY CHARGED SECONDARY COIL: f=40Hz
A=T, B=C, C=A+CHARGE, D=C+INJ. DURATION
INJ. CHARGED 2ms
TRIGGER 5ms
OUTPUT VOLTAGE (V)
30
25
20
15
10
5
0
−5
0
100
200
300
400
500
TIMING (UNIT)

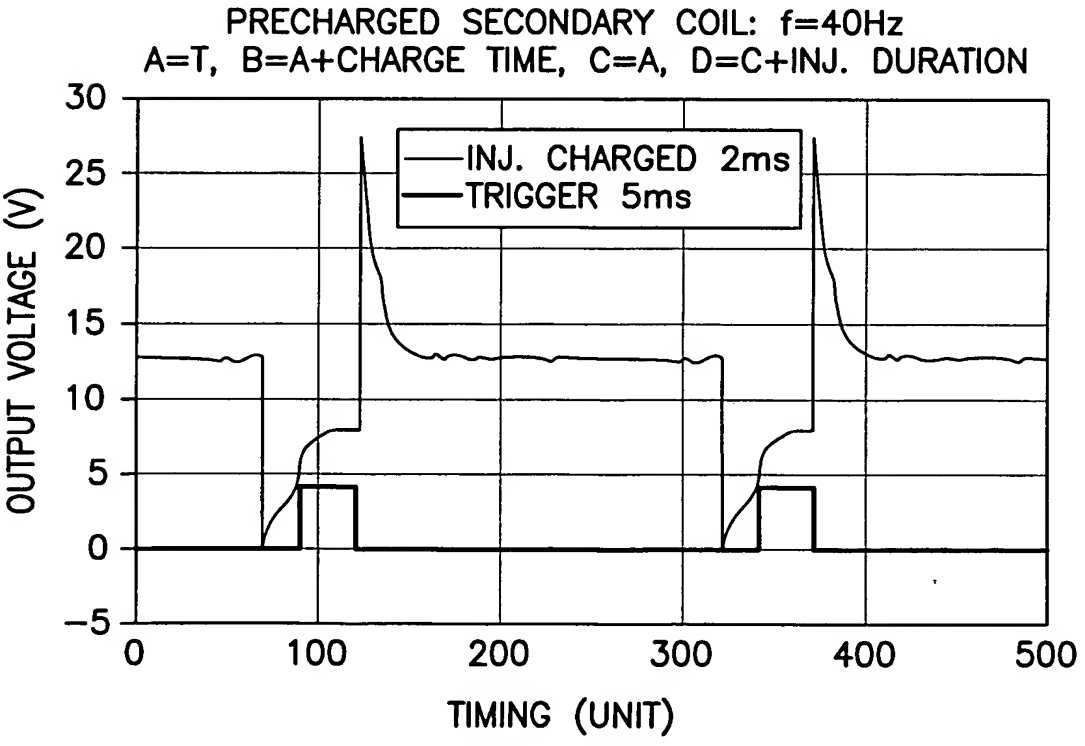

PRECHARGED SECONDARY COIL: f=40Hz
A=T, B=A+CHARGE TIME, C=A, D=C+INJ. DURATION
INJ. CHARGED 2ms
TRIGGER 5ms
OUTPUT VOLTAGE (V)
30
25
20
15
10
5
0
−5
0
100
200
300
400
500
TIMING (UNIT)

FIG.52

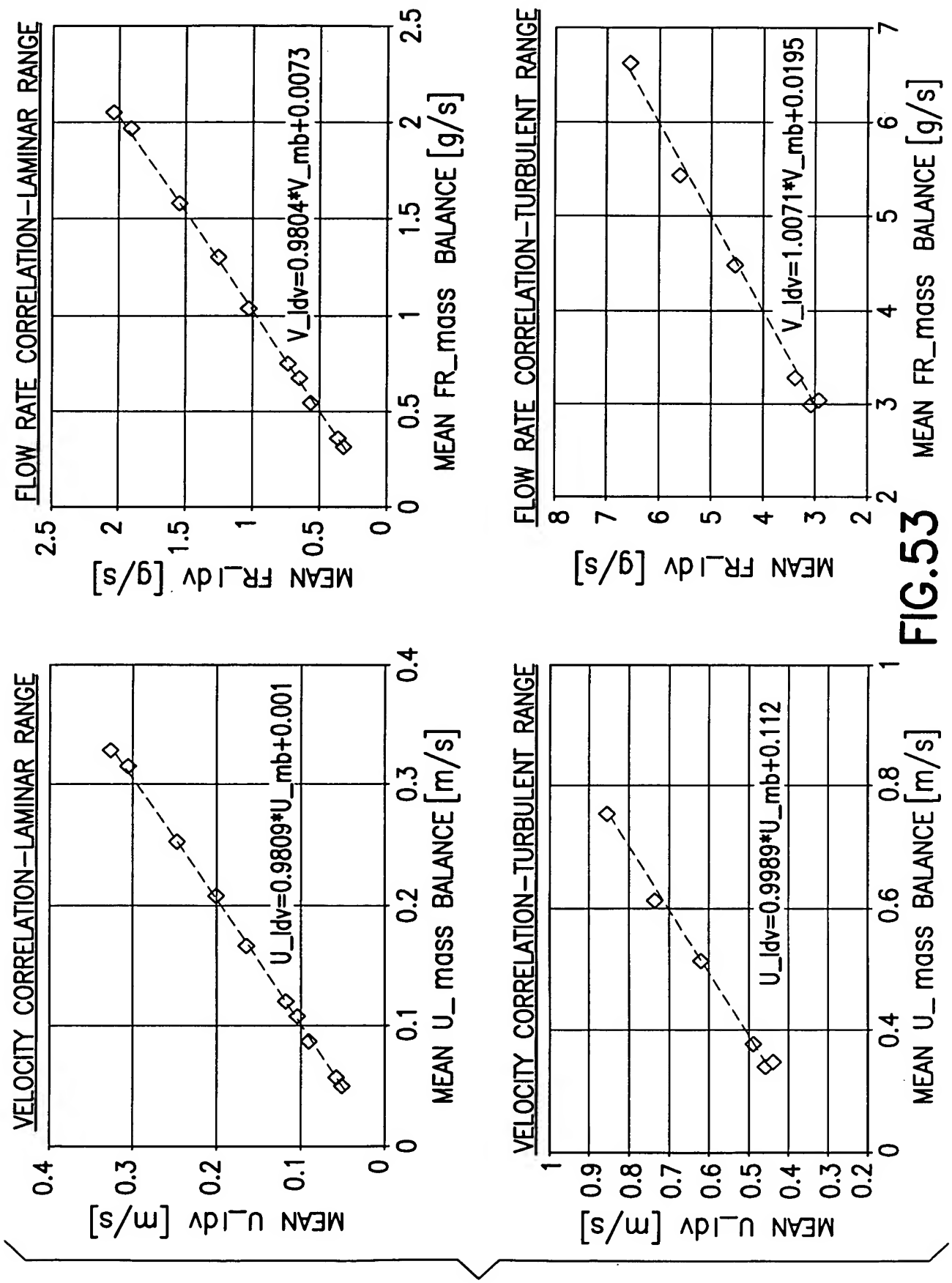

FLOW RATE CORRELATION–LAMINAR RANGE
MEAN FR_ldv [g/s]
MEAN FR_mass BALANCE [g/s]
V_ldv=0.9804*V_mb+0.0073
FLOW RATE CORRELATION–TURBULENT RANGE
MEAN FR_ldv [g/s]
MEAN FR_mass BALANCE [g/s]
V_ldv=1.0071*V_mb+0.0195
VELOCITY CORRELATION–LAMINAR RANGE
MEAN U_ldv [m/s]
MEAN U_ mass BALANCE [m/s]
U_ldv=0.9809*U_mb+0.001
VELOCITY CORRELATION–TURBULENT RANGE
MEAN U_ldv [m/s]
MEAN U_ mass BALANCE [m/s]
U_ldv=0.9989*U_mb+0.112

FIG.53

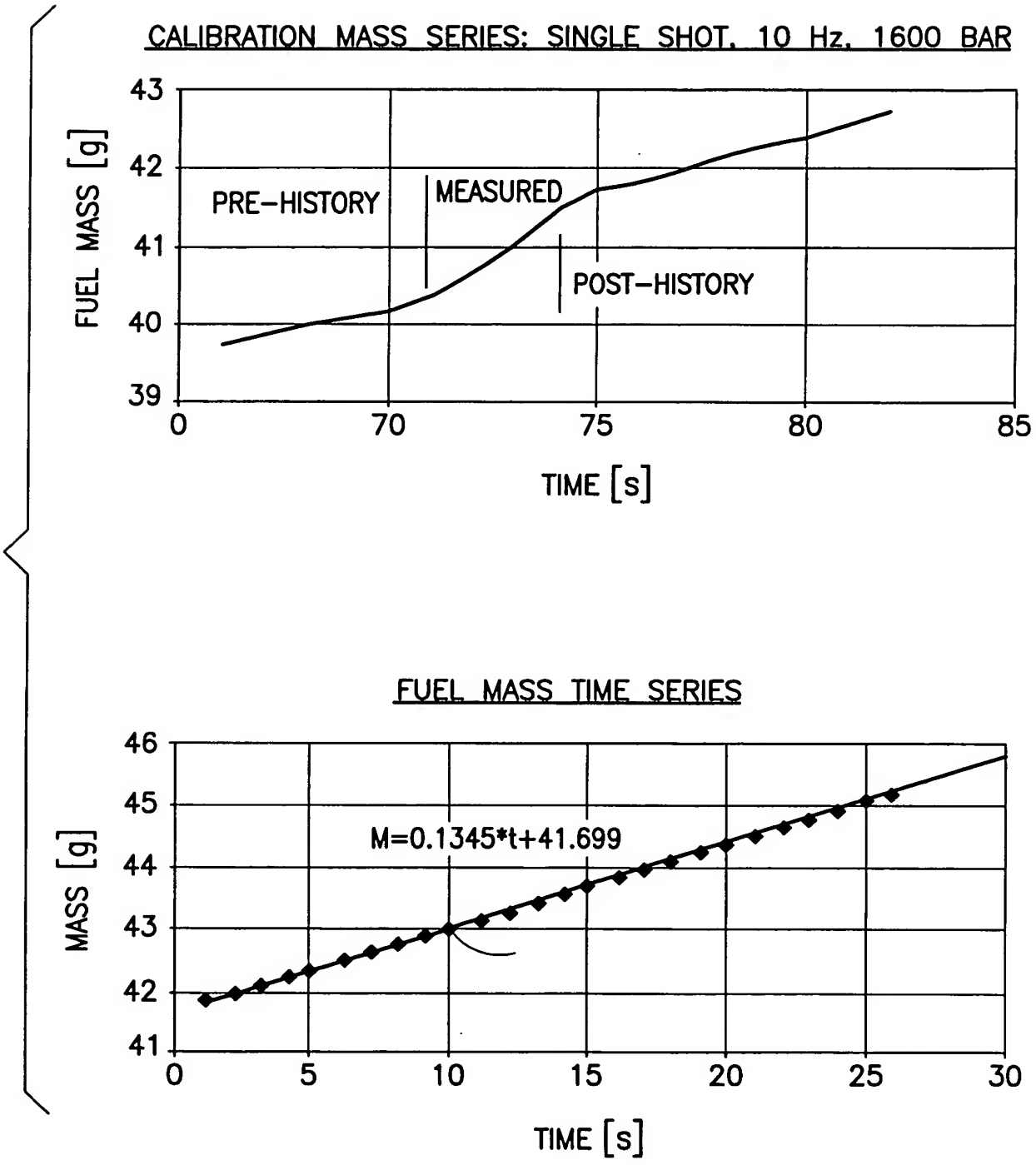

CALIBRATION MASS SERIES: SINGLE SHOT, 10 Hz, 1600 BAR
FUEL MASS [g]
43
42
41
40
39
PRE-HISTORY
MEASURED
POST-HISTORY
0
70
75
80
85
TIME [s]
FUEL MASS TIME SERIES
MASS [g]
46
45
44
43
42
41
M=0.1345*t+41.699
0
5
10
15
20
25
30
TIME [s]

FIG.54

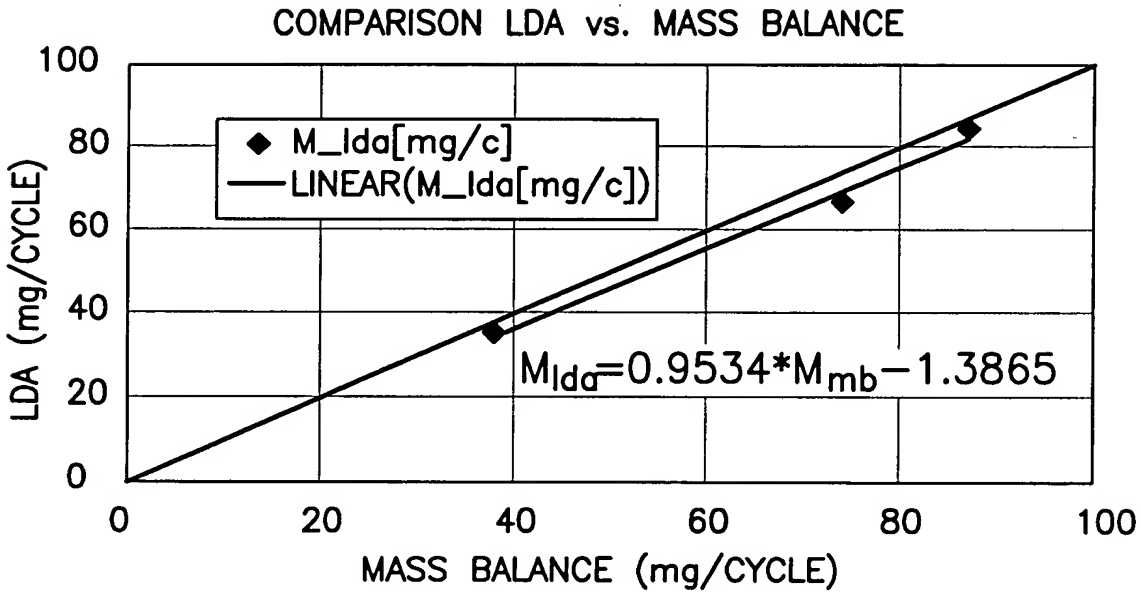

COMPARISON LDA vs. MASS BALANCE
100
80
60
40
20
0
LDA (mg/CYCLE)
M_lda[mg/c]
LINEAR(M_lda[mg/c])
$M_{lda}=0.9534*M_{mb}-1.3865$
0
20
40
60
80
100
MASS BALANCE (mg/CYCLE)

FIG.55

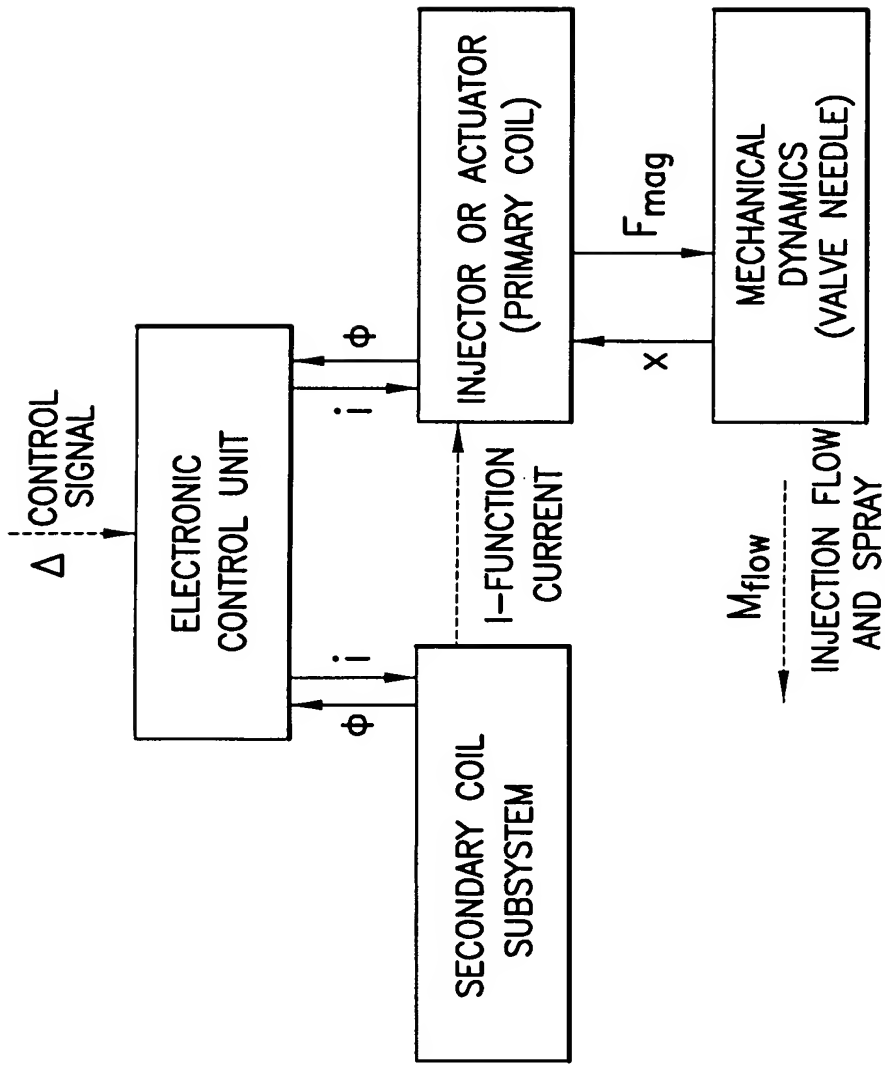

Δ CONTROL SIGNAL
ELECTRONIC CONTROL UNIT
i
Φ
i
Φ
SECONDARY COIL SUBSYSTEM
I-FUNCTION CURRENT
INJECTOR OR ACTUATOR (PRIMARY COIL)
F_{mag}
x
MECHANICAL DYNAMICS (VALVE NEEDLE)
M_{flow}
INJECTION FLOW AND SPRAY DYNAMICS

FIG.56

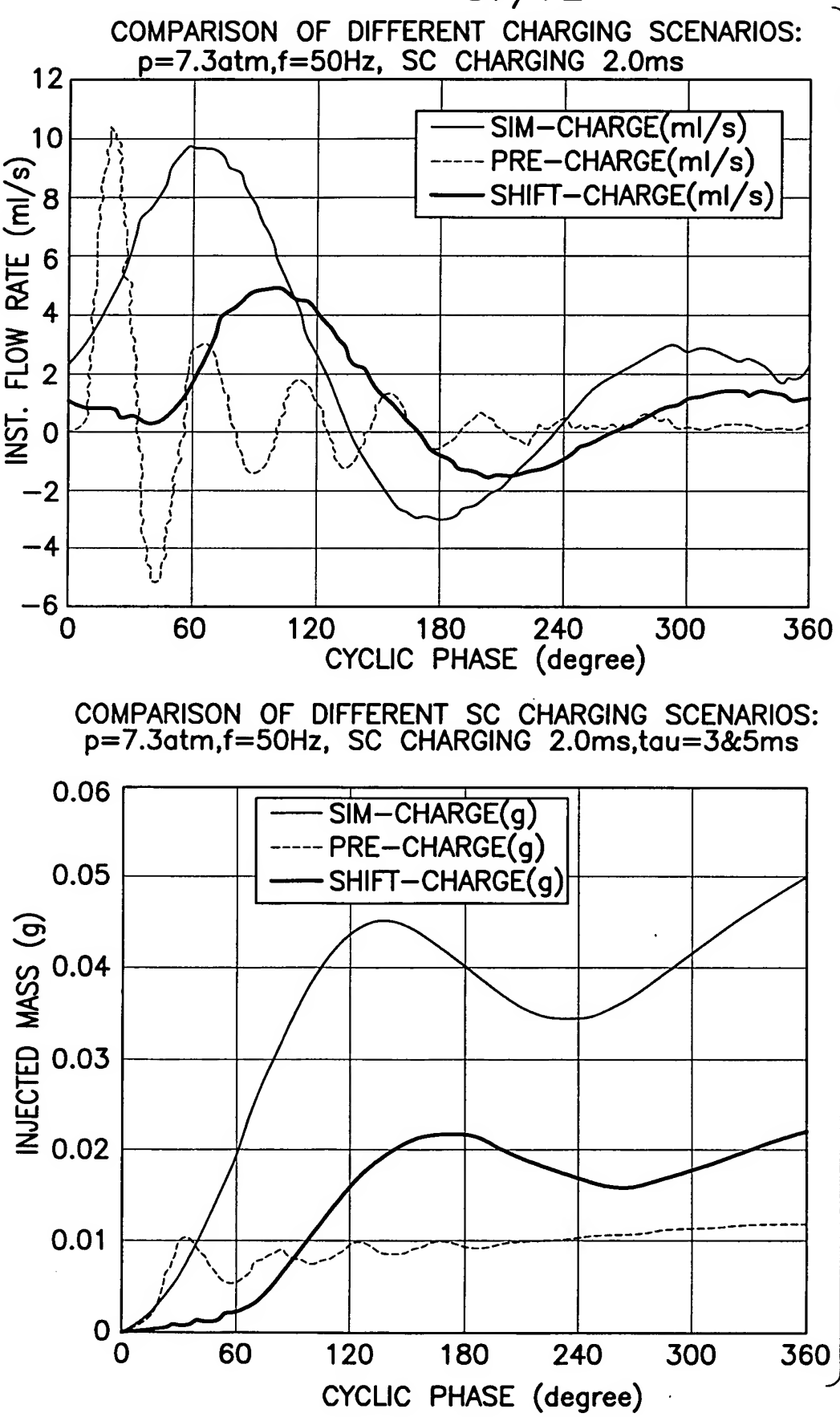

COMPARISON OF DIFFERENT CHARGING SCENARIOS:
p=7.3atm,f=50Hz, SC CHARGING 2.0ms
SIM-CHARGE(ml/s)
PRE-CHARGE(ml/s)
SHIFT-CHARGE(ml/s)
INST. FLOW RATE (ml/s)
12
10
8
6
4
2
0
-2
-4
-6
0
60
120
180
240
300
360
CYCLIC PHASE (degree)
COMPARISON OF DIFFERENT SC CHARGING SCENARIOS:
p=7.3atm,f=50Hz, SC CHARGING 2.0ms,tau=3&5ms
SIM-CHARGE(g)
PRE-CHARGE(g)
SHIFT-CHARGE(g)
INJECTED MASS (g)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
60
120
180
240
300
360
CYCLIC PHASE (degree)

FIG.57

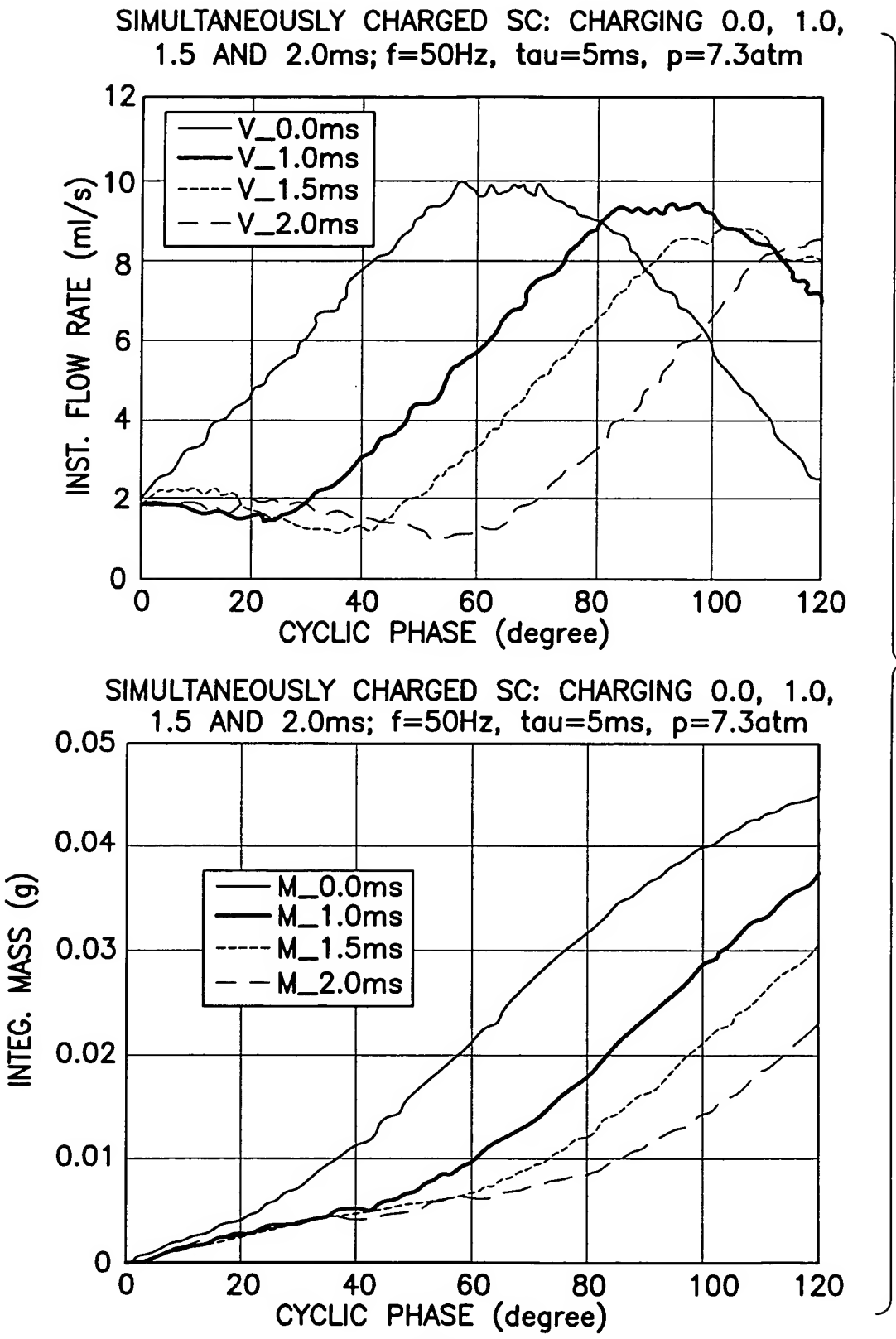

SIMULTANEOUSLY CHARGED SC: CHARGING 0.0, 1.0, 1.5 AND 2.0ms; f=50Hz, tau=5ms, p=7.3atm
INST. FLOW RATE (ml/s)
V_0.0ms
V_1.0ms
V_1.5ms
V_2.0ms
CYCLIC PHASE (degree)
SIMULTANEOUSLY CHARGED SC: CHARGING 0.0, 1.0, 1.5 AND 2.0ms; f=50Hz, tau=5ms, p=7.3atm
INTEG. MASS (g)
M_0.0ms
M_1.0ms
M_1.5ms
M_2.0ms
CYCLIC PHASE (degree)

FIG.58A

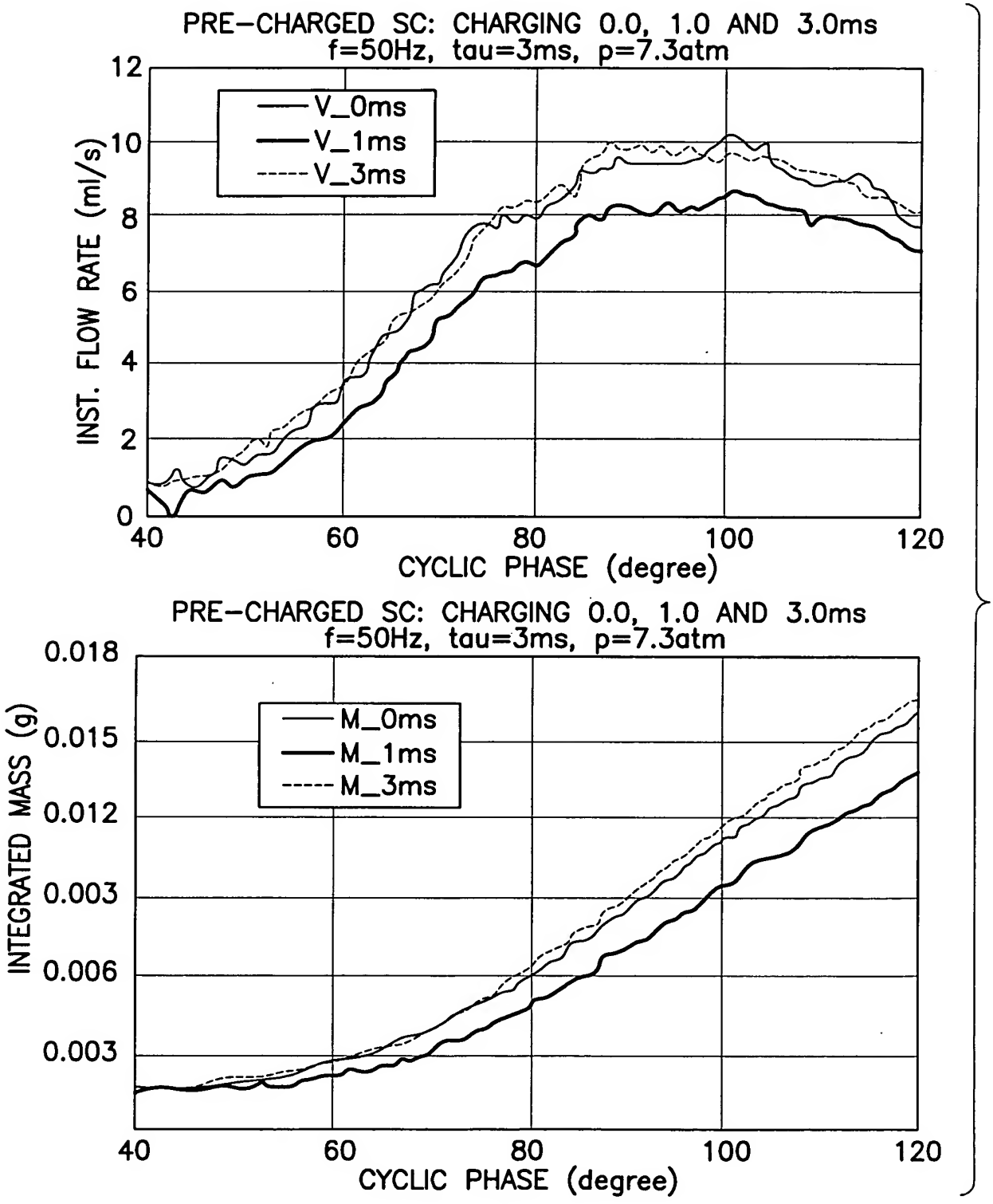

PRE-CHARGED SC: CHARGING 0.0, 1.0 AND 3.0ms
f=50Hz, tau=3ms, p=7.3atm
V_0ms
V_1ms
V_3ms
INST. FLOW RATE (ml/s)
0
2
4
6
8
10
12
40
60
80
100
120
CYCLIC PHASE (degree)
PRE-CHARGED SC: CHARGING 0.0, 1.0 AND 3.0ms
f=50Hz, tau=3ms, p=7.3atm
M_0ms
M_1ms
M_3ms
INTEGRATED MASS (g)
0.003
0.006
0.003
0.012
0.015
0.018
40
60
80
100
120
CYCLIC PHASE (degree)

FIG.58B

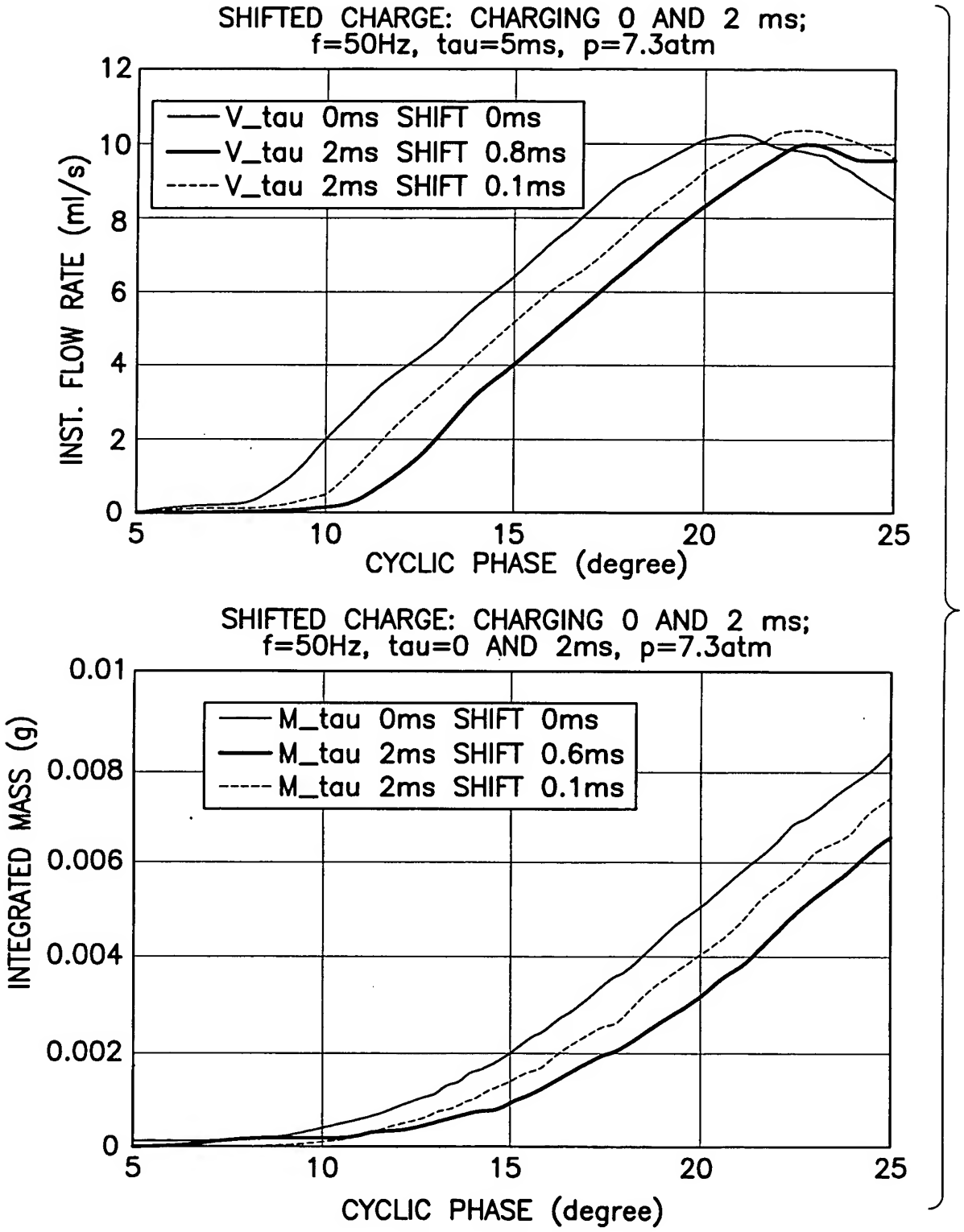

SHIFTED CHARGE: CHARGING 0 AND 2 ms;
f=50Hz, tau=5ms, p=7.3atm
V_tau 0ms SHIFT 0ms
V_tau 2ms SHIFT 0.8ms
V_tau 2ms SHIFT 0.1ms
INST. FLOW RATE (ml/s)
CYCLIC PHASE (degree)
SHIFTED CHARGE: CHARGING 0 AND 2 ms;
f=50Hz, tau=0 AND 2ms, p=7.3atm
M_tau 0ms SHIFT 0ms
M_tau 2ms SHIFT 0.6ms
M_tau 2ms SHIFT 0.1ms
INTEGRATED MASS (g)
CYCLIC PHASE (degree)

FIG.58C

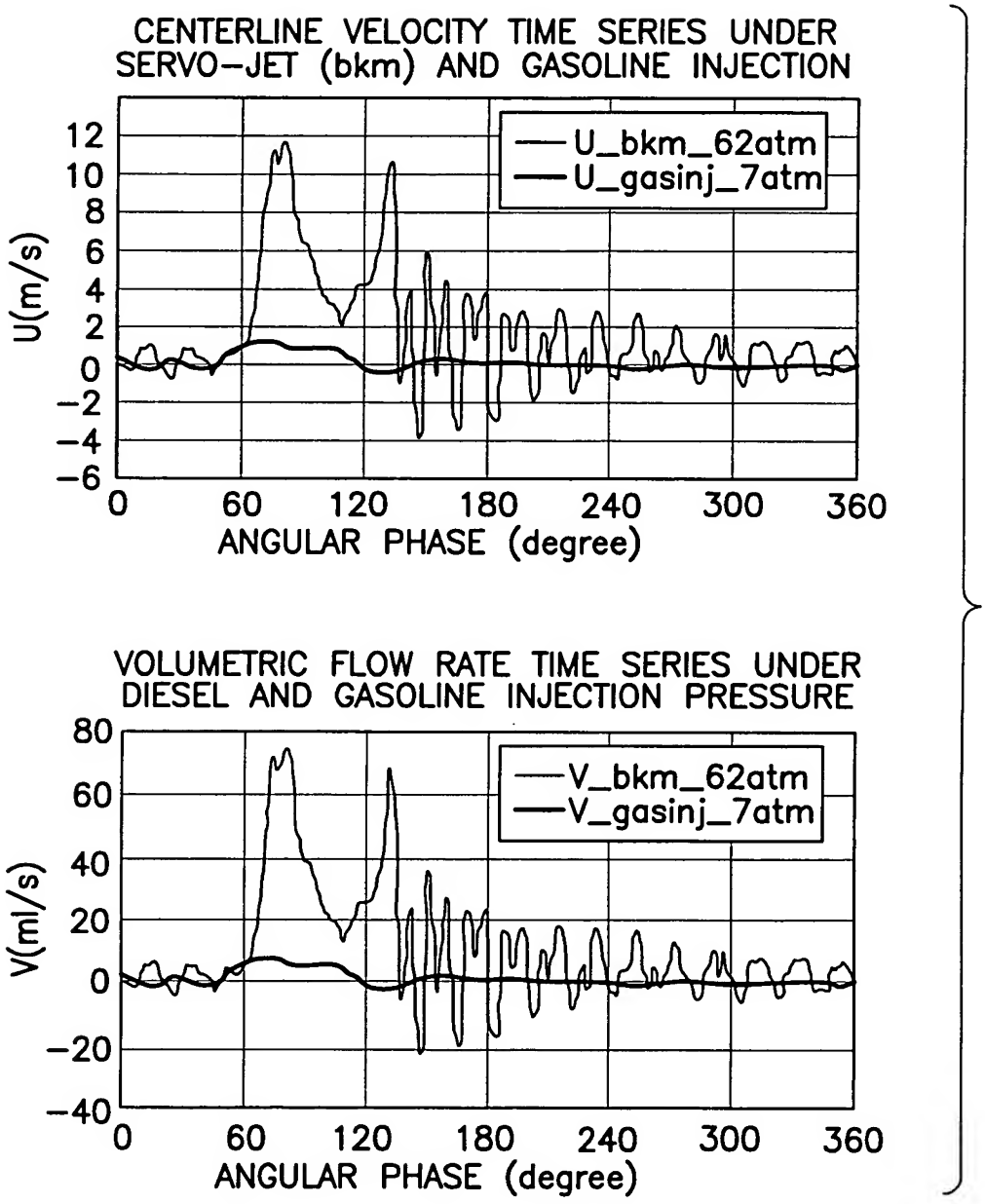

CENTERLINE VELOCITY TIME SERIES UNDER SERVO-JET (bkm) AND GASOLINE INJECTION
U_bkm_62atm
U_gasinj_7atm
U(m/s)
12
10
8
6
4
2
0
-2
-4
-6
0
60
120
180
240
300
360
ANGULAR PHASE (degree)
VOLUMETRIC FLOW RATE TIME SERIES UNDER DIESEL AND GASOLINE INJECTION PRESSURE
V_bkm_62atm
V_gasinj_7atm
V(ml/s)
80
60
40
20
0
-20
-40
0
60
120
180
240
300
360
ANGULAR PHASE (degree)

FIG.59

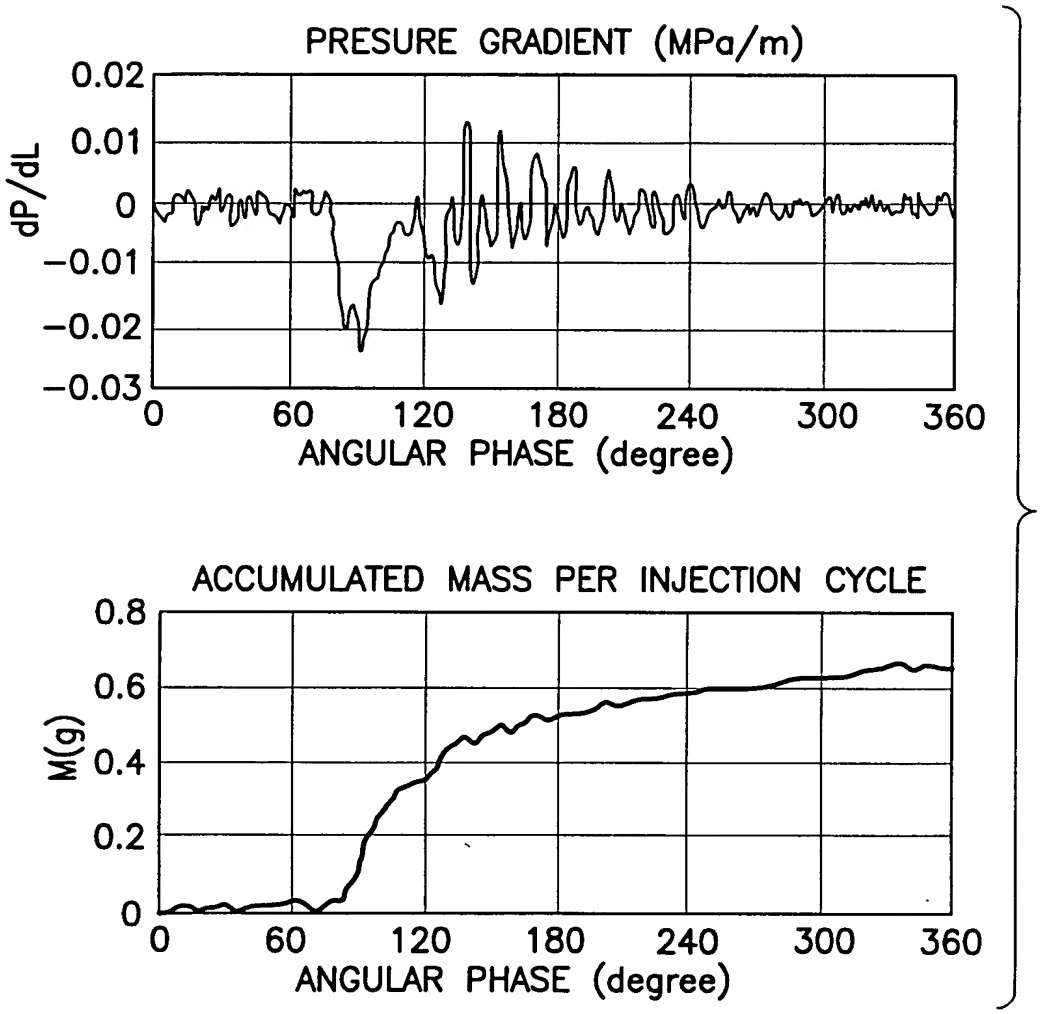

PRESURE GRADIENT (MPa/m)
dP/dL
0.02
0.01
0
−0.01
−0.02
−0.03
0
60
120
180
240
300
360
ANGULAR PHASE (degree)
ACCUMULATED MASS PER INJECTION CYCLE
M(g)
0.8
0.6
0.4
0.2
0
0
60
120
180
240
300
360
ANGULAR PHASE (degree)

FIG.60

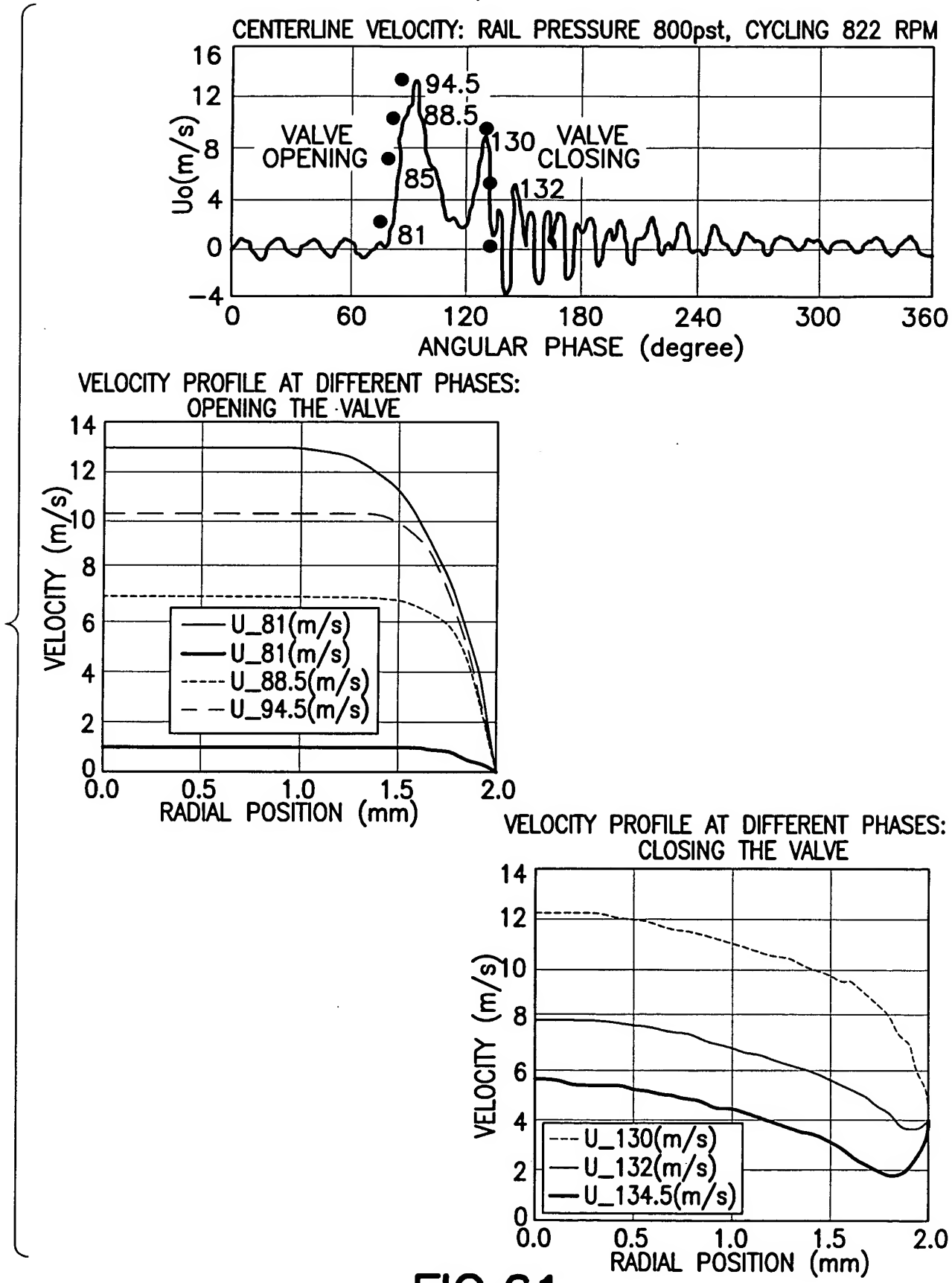

CENTERLINE VELOCITY: RAIL PRESSURE 800pst, CYCLING 822 RPM
Uo(m/s)
16
12
8
4
0
−4
94.5
88.5
130
VALVE OPENING
VALVE CLOSING
85
132
81
0
60
120
180
240
300
360
ANGULAR PHASE (degree)
VELOCITY PROFILE AT DIFFERENT PHASES:
OPENING THE VALVE
VELOCITY (m/s)
14
12
10
8
6
4
2
0
U_81(m/s)
U_81(m/s)
U_88.5(m/s)
U_94.5(m/s)
0.0
0.5
1.0
1.5
2.0
RADIAL POSITION (mm)
VELOCITY PROFILE AT DIFFERENT PHASES:
CLOSING THE VALVE
VELOCITY (m/s)
14
12
10
8
6
4
2
0
U_130(m/s)
U_132(m/s)
U_134.5(m/s)
0.0
0.5
1.0
1.5
2.0
RADIAL POSITION (mm)

FIG.61

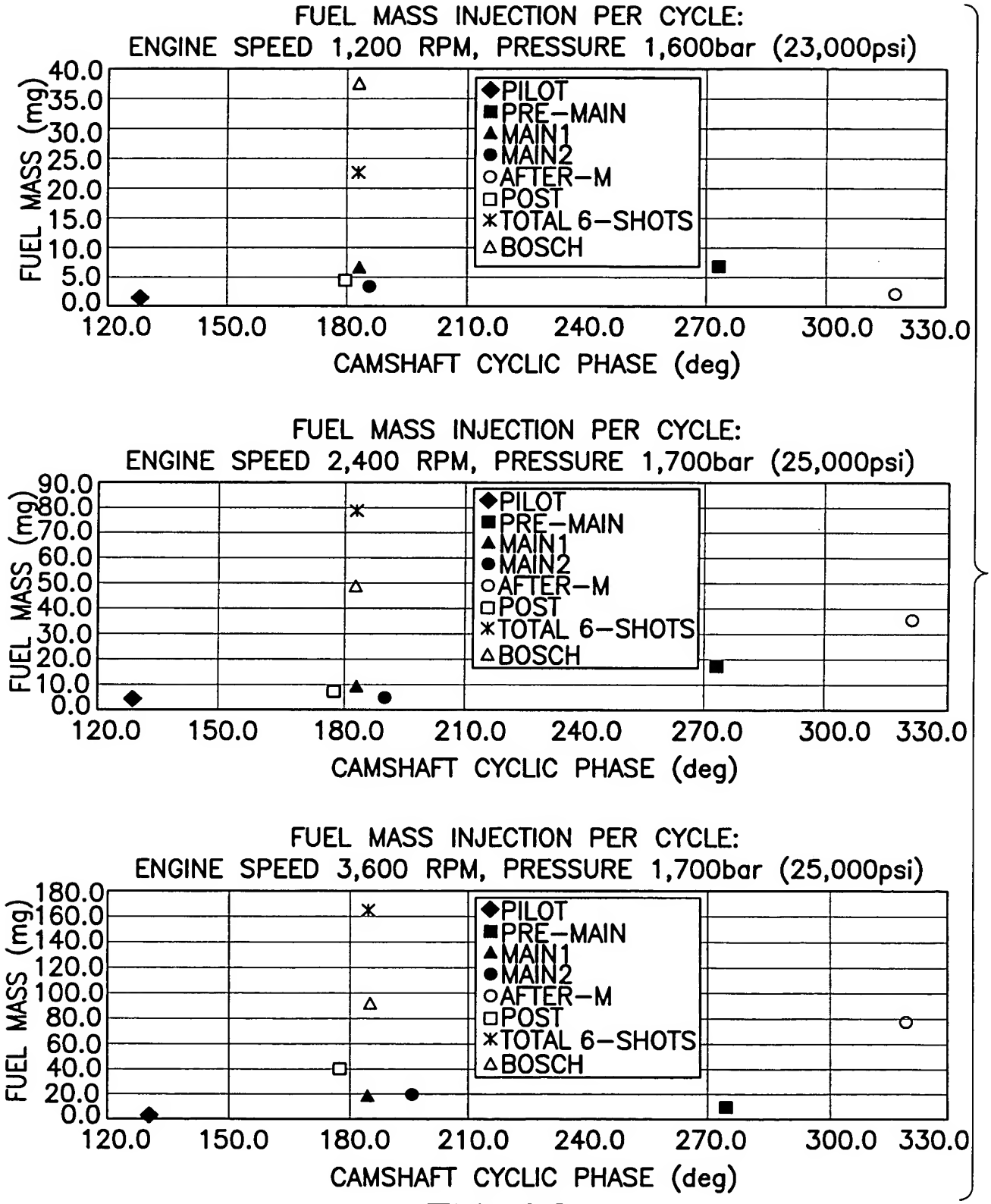

FUEL MASS INJECTION PER CYCLE:
ENGINE SPEED 1,200 RPM, PRESSURE 1,600bar (23,000psi)
FUEL MASS (mg)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
PILOT
PRE-MAIN
MAIN1
MAIN2
AFTER-M
POST
TOTAL 6-SHOTS
BOSCH
120.0
150.0
180.0
210.0
240.0
270.0
300.0
330.0
CAMSHAFT CYCLIC PHASE (deg)
FUEL MASS INJECTION PER CYCLE:
ENGINE SPEED 2,400 RPM, PRESSURE 1,700bar (25,000psi)
FUEL MASS (mg)
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
PILOT
PRE-MAIN
MAIN1
MAIN2
AFTER-M
POST
TOTAL 6-SHOTS
BOSCH
120.0
150.0
180.0
210.0
240.0
270.0
300.0
330.0
CAMSHAFT CYCLIC PHASE (deg)
FUEL MASS INJECTION PER CYCLE:
ENGINE SPEED 3,600 RPM, PRESSURE 1,700bar (25,000psi)
FUEL MASS (mg)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
PILOT
PRE-MAIN
MAIN1
MAIN2
AFTER-M
POST
TOTAL 6-SHOTS
BOSCH
120.0
150.0
180.0
210.0
240.0
270.0
300.0
330.0
CAMSHAFT CYCLIC PHASE (deg)

FIG.62

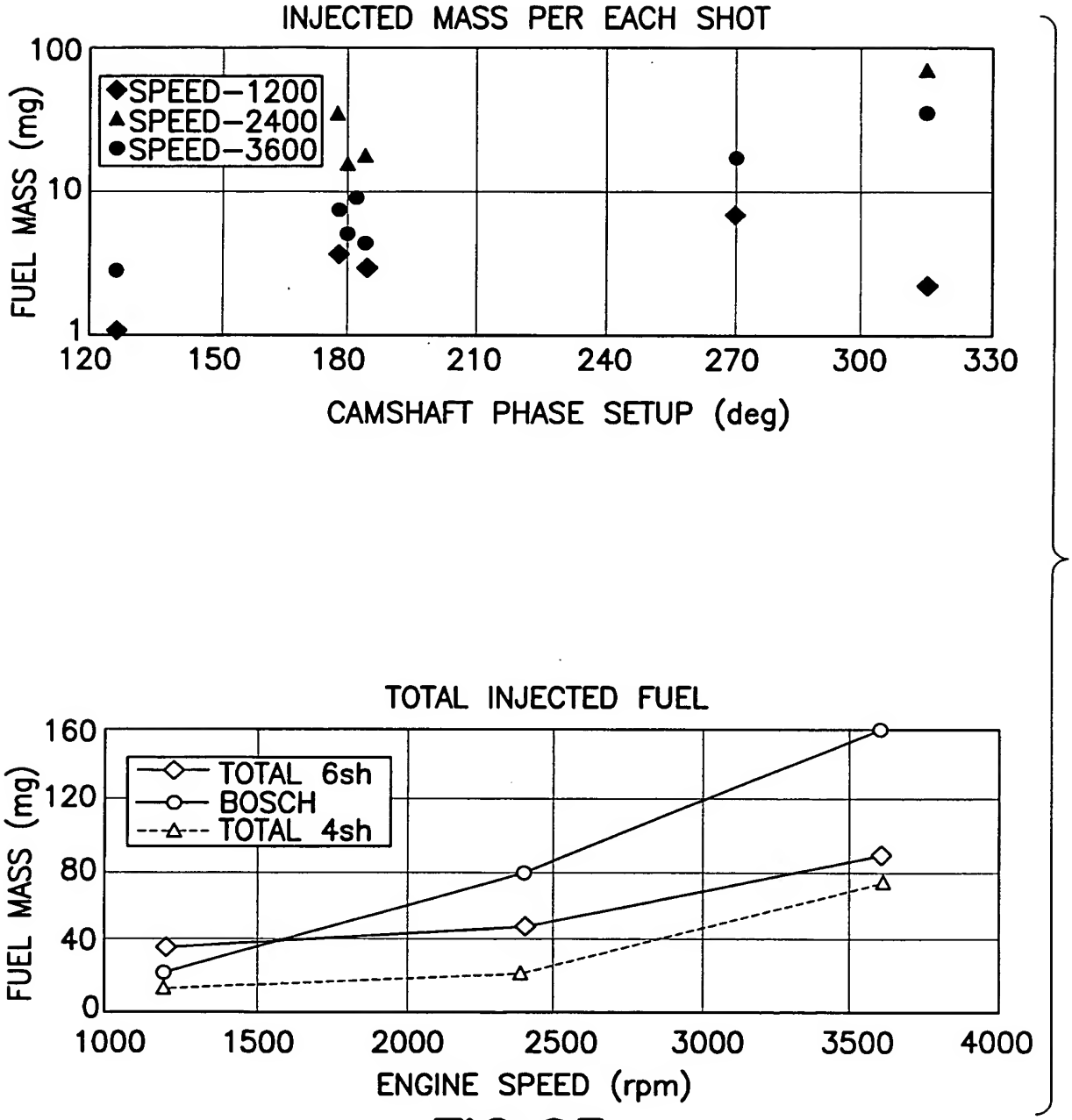

INJECTED MASS PER EACH SHOT
100
10
1
FUEL MASS (mg)
SPEED–1200
SPEED–2400
SPEED–3600
120
150
180
210
240
270
300
330
CAMSHAFT PHASE SETUP (deg)
TOTAL INJECTED FUEL
160
120
80
40
0
FUEL MASS (mg)
TOTAL 6sh
BOSCH
TOTAL 4sh
1000
1500
2000
2500
3000
3500
4000
ENGINE SPEED (rpm)

FIG.63

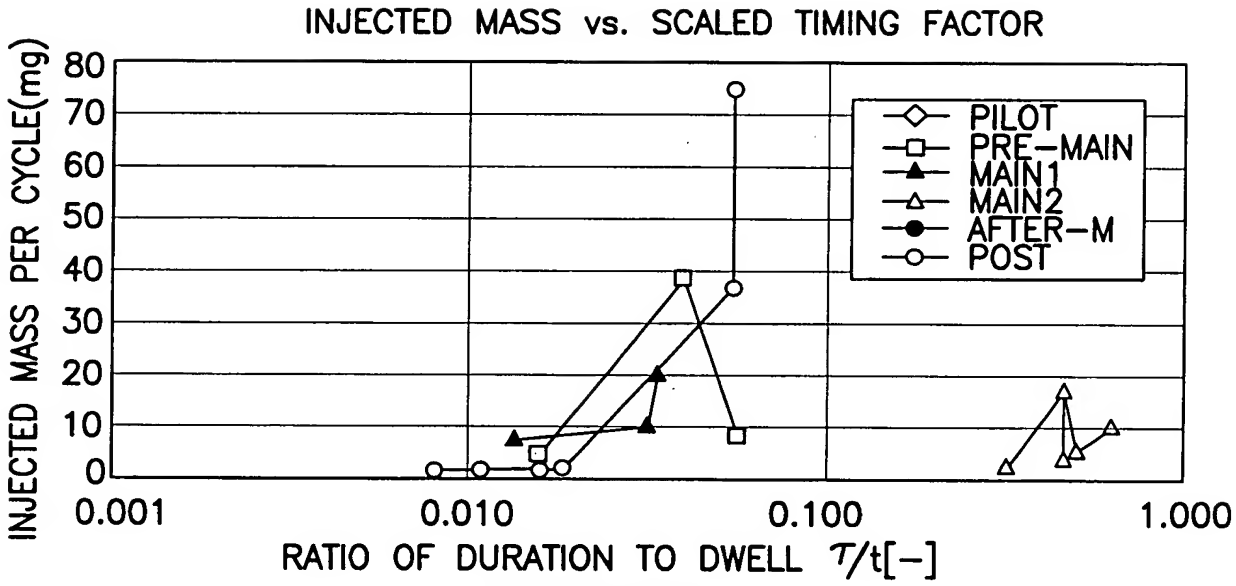

INJECTED MASS vs. SCALED TIMING FACTOR
INJECTED MASS PER CYCLE(mg)
80
70
60
50
40
30
20
10
0
0.001
0.010
0.100
1.000
RATIO OF DURATION TO DWELL τ/t[−]
PILOT
PRE−MAIN
MAIN1
MAIN2
AFTER−M
POST

FIG.64

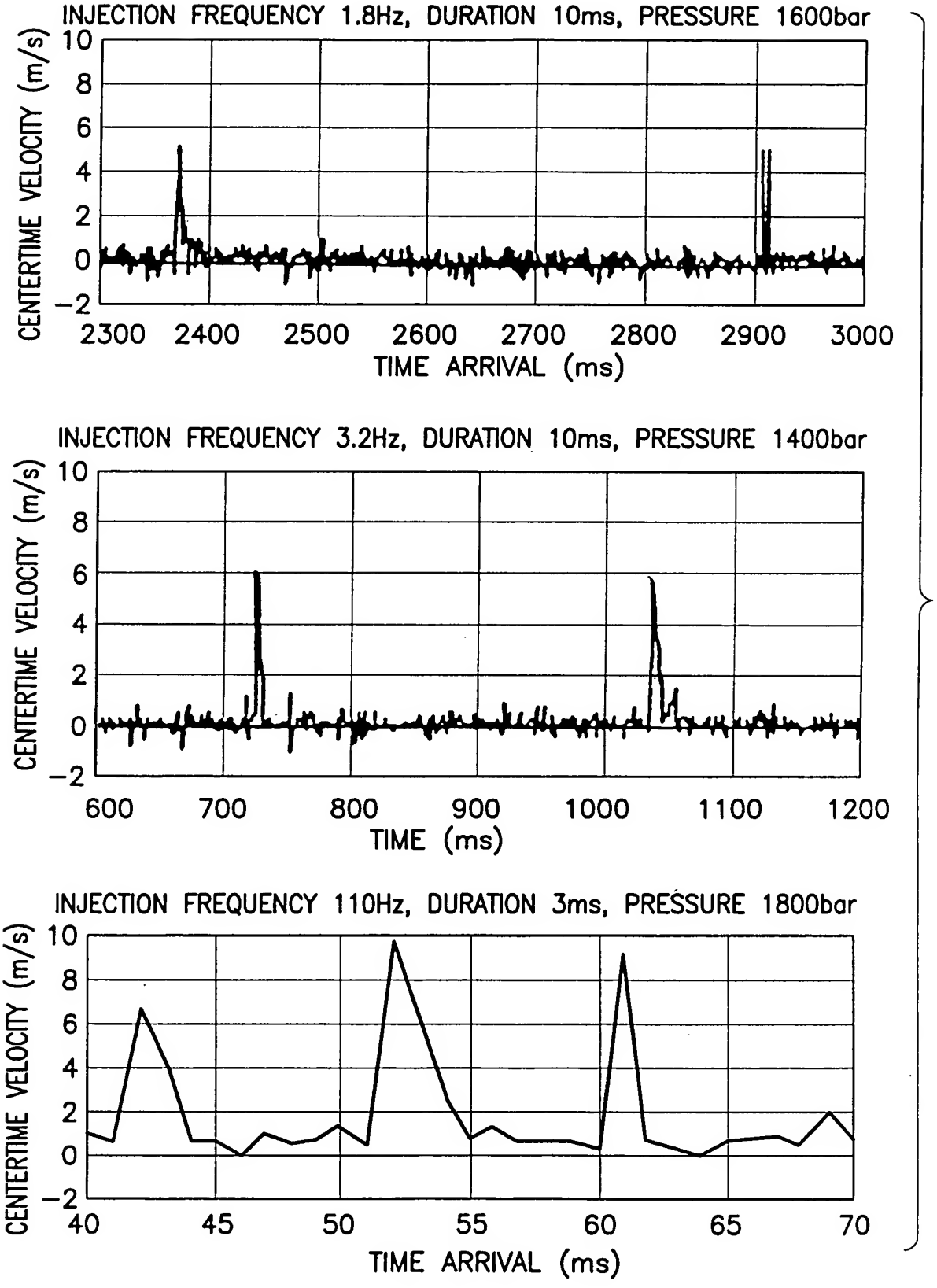

INJECTION FREQUENCY 1.8Hz, DURATION 10ms, PRESSURE 1600bar
CENTERTIME VELOCITY (m/s)
10
8
6
4
2
0
−2
2300
2400
2500
2600
2700
2800
2900
3000
TIME ARRIVAL (ms)
INJECTION FREQUENCY 3.2Hz, DURATION 10ms, PRESSURE 1400bar
CENTERTIME VELOCITY (m/s)
10
8
6
4
2
0
−2
600
700
800
900
1000
1100
1200
TIME (ms)
INJECTION FREQUENCY 110Hz, DURATION 3ms, PRESSURE 1800bar
CENTERTIME VELOCITY (m/s)
10
8
6
4
2
0
−2
40
45
50
55
60
65
70
TIME ARRIVAL (ms)

FIG.65

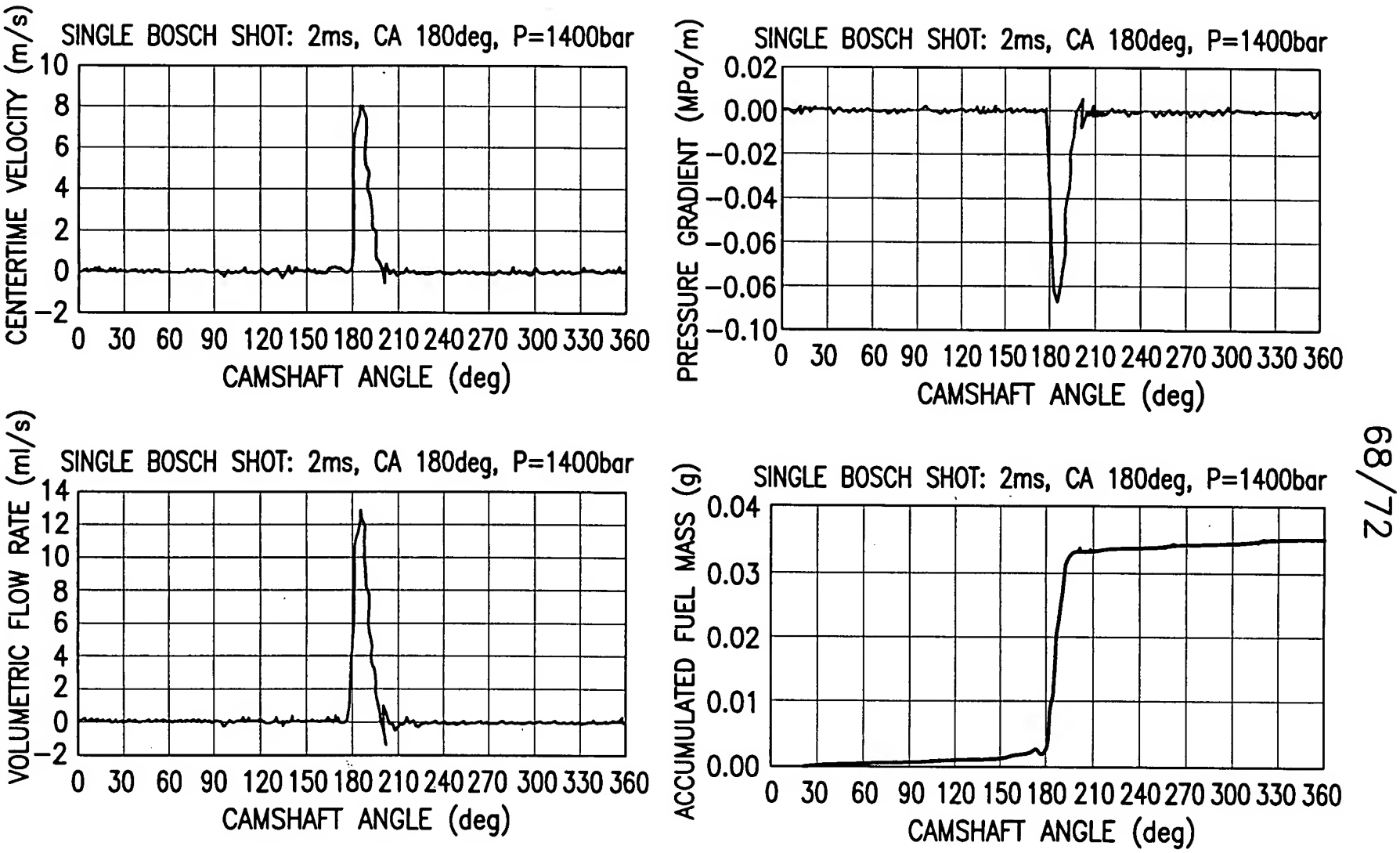

SINGLE BOSCH SHOT: 2ms, CA 180deg, P=1400bar
CENTERTIME VELOCITY (m/s)
10
8
6
4
2
0
−2
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE BOSCH SHOT: 2ms, CA 180deg, P=1400bar
PRESSURE GRADIENT (MPa/m)
0.02
0.00
−0.02
−0.04
−0.06
−0.06
−0.10
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE BOSCH SHOT: 2ms, CA 180deg, P=1400bar
VOLUMETRIC FLOW RATE (ml/s)
14
12
10
8
6
4
2
0
−2
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE BOSCH SHOT: 2ms, CA 180deg, P=1400bar
ACCUMULATED FUEL MASS (g)
0.04
0.03
0.02
0.01
0.00
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)

FIG.66

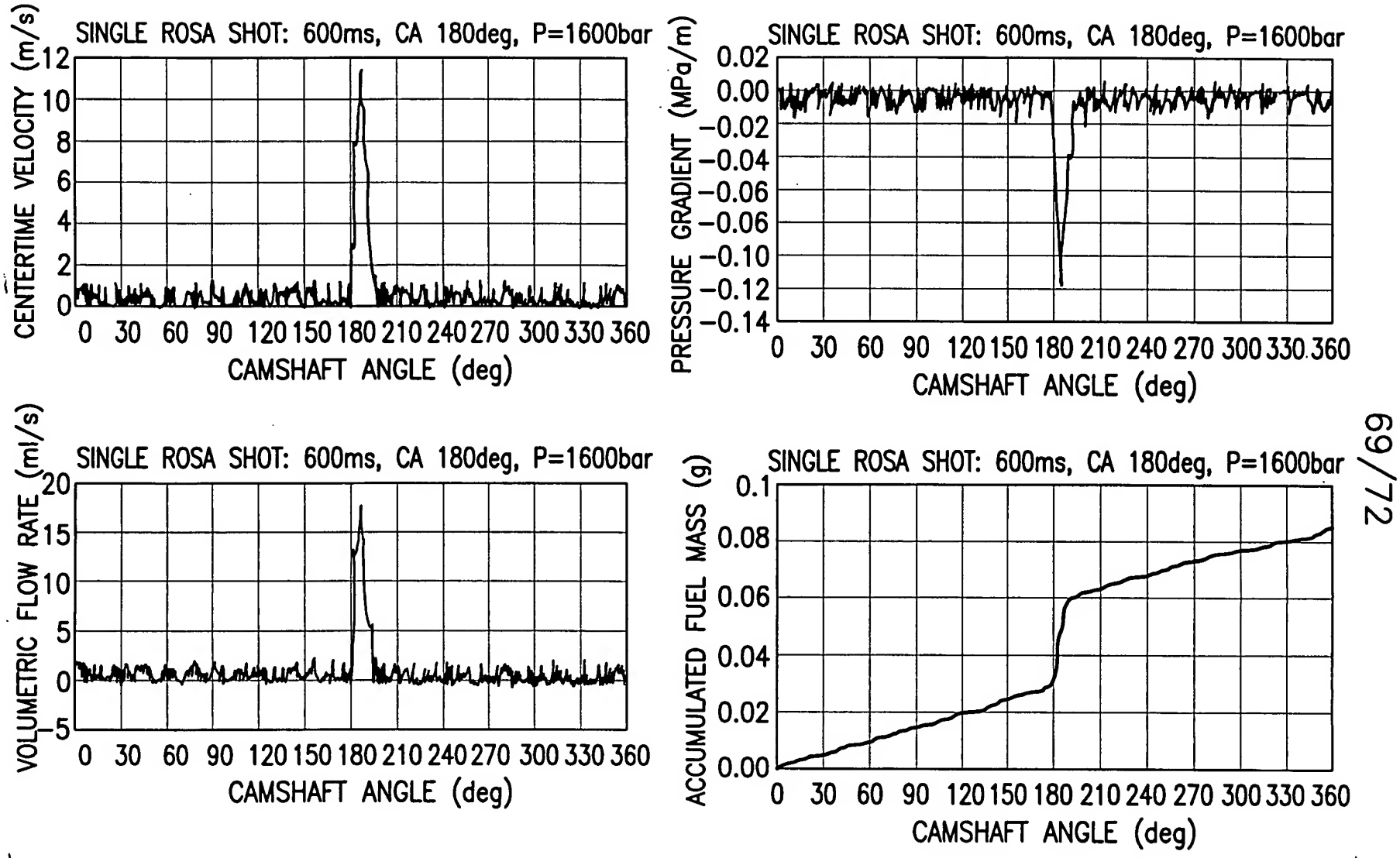

SINGLE ROSA SHOT: 600ms, CA 180deg, P=1600bar
CENTERTIME VELOCITY (m/s)
12
10
8
6
4
2
0
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE ROSA SHOT: 600ms, CA 180deg, P=1600bar
PRESSURE GRADIENT (MPa/m)
0.02
0.00
−0.02
−0.04
−0.06
−0.06
−0.10
−0.12
−0.14
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE ROSA SHOT: 600ms, CA 180deg, P=1600bar
VOLUMETRIC FLOW RATE (ml/s)
20
15
10
5
0
−5
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
SINGLE ROSA SHOT: 600ms, CA 180deg, P=1600bar
ACCUMULATED FUEL MASS (g)
0.1
0.08
0.06
0.04
0.02
0.00
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)

FIG.67

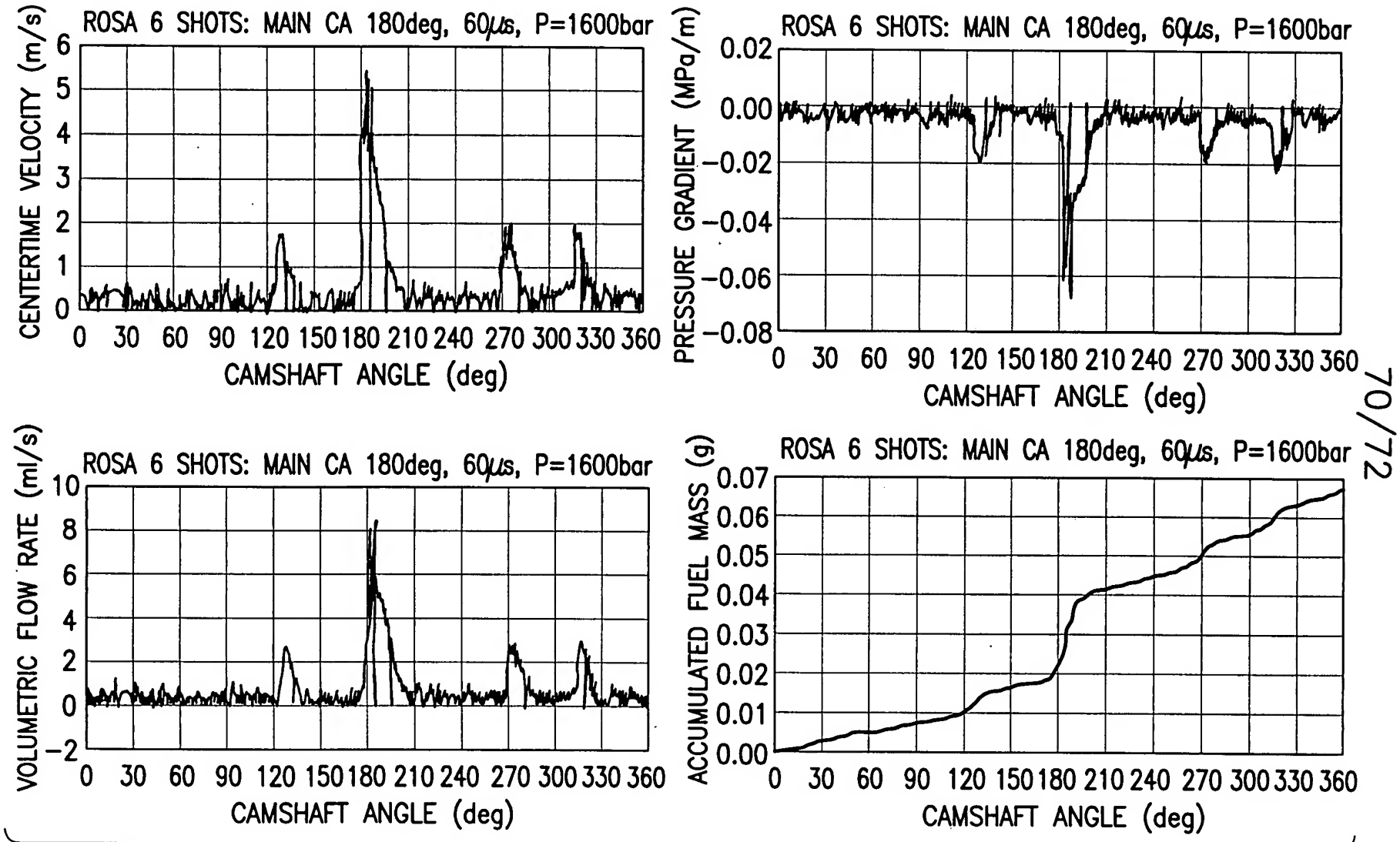

ROSA 6 SHOTS: MAIN CA 180deg, 60μs, P=1600bar
CENTERTIME VELOCITY (m/s)
0 1 2 3 4 5 6
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
ROSA 6 SHOTS: MAIN CA 180deg, 60μs, P=1600bar
PRESSURE GRADIENT (MPa/m)
0.02 0.00 −0.02 −0.04 −0.06 −0.08
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
ROSA 6 SHOTS: MAIN CA 180deg, 60μs, P=1600bar
VOLUMETRIC FLOW RATE (ml/s)
10 8 6 4 2 0 −2
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)
ROSA 6 SHOTS: MAIN CA 180deg, 60μs, P=1600bar
ACCUMULATED FUEL MASS (g)
0.07 0.06 0.05 0.04 0.03 0.02 0.01 0.00
0 30 60 90 120 150 180 210 240 270 300 330 360
CAMSHAFT ANGLE (deg)

FIG.68

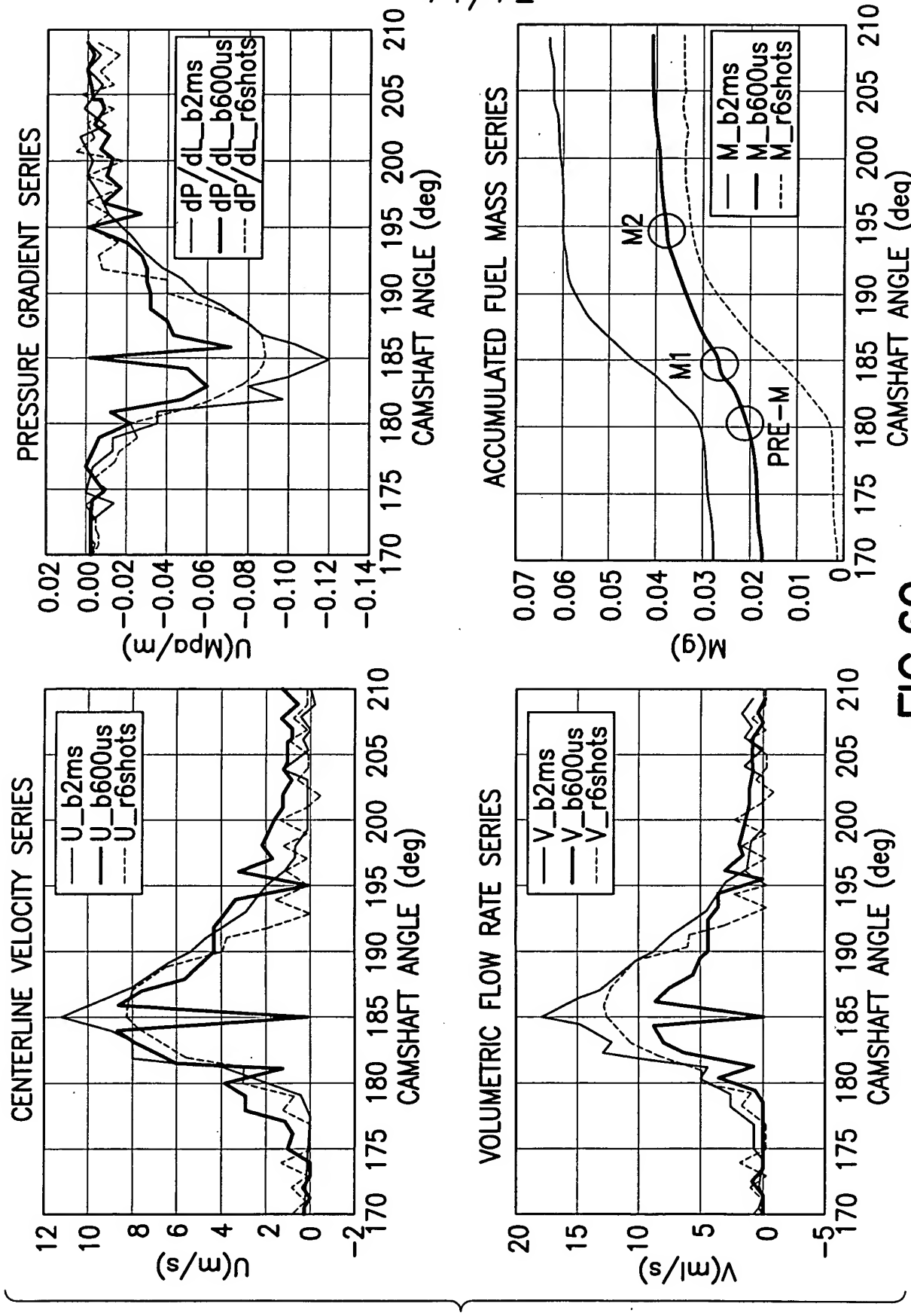

PRESSURE GRADIENT SERIES
dP/dL_b2ms
dP/dL_b600us
dP/dL_r6shots
U(Mpa/m)
CAMSHAFT ANGLE (deg)
ACCUMULATED FUEL MASS SERIES
M_b2ms
M_b600us
M_r6shots
M2
M1
PRE-M
M(g)
CAMSHAFT ANGLE (deg)
CENTERLINE VELOCITY SERIES
U_b2ms
U_b600us
U_r6shots
U(m/s)
CAMSHAFT ANGLE (deg)
VOLUMETRIC FLOW RATE SERIES
V_b2ms
V_b600us
V_r6shots
V(ml/s)
CAMSHAFT ANGLE (deg)

FIG.69

	SHOT/PASS	START deg	END deg	DURATION ms	MASSES mg	% OF TOTAL %
1	DELIVER 1	0	125	34.72	10.74	14.8
2	PILOT	125	133	2.22	4.18	5.8
3	DELIVER 2	133	175	11.67	4.33	6.0
4	PRE-MAIN	175	182	1.94	4.47	6.2
5	MAIN 1	182	186	1.11	7.30	10.1
6	MAIN 2	186	196	2.78	11.65	16.1
7	DELIVER 3	196	269	20.28	10.62	14.7
8	AFTER-M	269	281	3.33	5.81	8.0
9	DELIVER 4	281	315	9.44	5.02	6.9
10	POST	315	327	3.33	4.76	6.6
11	DELIVER 5	327	360	9.17	3.54	4.9
	TOTAL:				72.42	100.0
	INJECTED				38.17	52.7
	DELIVER				34.25	47.3

FIG.70